Infants’ Sensitivity to Time-Speed-Distance Interrelations

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Zusammenfassung

Die Zusammenhänge von Zeit, Geschwindigkeit und Distanz definieren jegliche Bewegungen des eigenen Körpers sowie von Objekten in der Welt. Obwohl bereits Säuglinge beständig Objektbewegungen erleben, sind der ontogenetische Ursprung und der Entwicklungsverlauf dieses Verständnisses weitgehend unerforscht. Die folgenden Studien untersuchten, wann und wie sich das frühkindliche Verständnis über diese Zusammenhänge entwickelt. Ein Teil der vorliegenden Experimente untersuchte 6 und 10 Monate alte Säuglinge hinsichtlich ihrer Fähigkeit, verschiedene Geschwindigkeiten zu unterscheiden. Es konnte gezeigt werden, dass die Diskrimination von Geschwindigkeiten dem Weberschen Gesetz unterliegt, was mit Ergebnissen zur Zeit- und Raumdiskriminierung bei Säuglingen einhergeht. Es scheint, dass sowohl Zeit, Raum als auch Geschwindigkeit von einem gemeinsamen zugrundeliegenden Mechanismus repräsentiert werden. Ein anderer Teil der Experimente untersuchte die frühkindliche Sensitivität für die Zusammenhänge von Zeit, Geschwindigkeit und Distanz bei 12, 18 und 24 Monate alten Säuglingen. Nachdem sie Informationen über die Zeit und Geschwindigkeit der Bewegung bekamen, konnten 18 Monate alte Säuglinge korrekt auf zurückgelegte Distanzen schlussfolgern. Diese Inferenzen waren jedoch stark kontextabhängig, da die Dauer, mit der ein Objekt verdeckt wurde, einen Einfluss auf die frühkindlichen Inferenzen hatte. Derselbe Einfluss zeigte sich im Alter von 24 Monaten nicht mehr, was darauf hinweist, dass die kindlichen Repräsentationen mit zunehmendem Alter robuster werden. In einer weiteren Studie zeigte sich, dass 12 Monate alte Säuglinge nicht korrekt auf Distanzen schlussfolgern können. Es kann konstatiert werden, dass sich die Fähigkeiten zur Integration von Zeit- und Geschwindigkeitsinformationen und die korrekte Schlussfolgerung auf Distanz im Verlauf der ersten 18 Lebensmonate auszubilden scheinen.

Summary

Time-speed-distance interrelations are inherent in every movement of the own body as well as every object in the world. Although we are confronted with moving objects from an early age on, the ontogenetic origin and developmental course of humans' sensitivity to these interrelations remains unclear. The following studies explored infants' understanding of the relations between these dimensions and thus, shed light on the development of this particular knowledge. The first set of experiments investigated 6- and 10-month-old infants' ability to discriminate between different speeds. The findings suggest that infants' speed discrimination is subject to Weber's law, which parallels previous results about infants' discrimination of time and space. Thus, results indicate that time, space, and speed are represented by a common underlying mechanism and/or comparison process. Another set of experiments explored 12-, 18-, and 24-month-old infants' sensitivity to time-speed-distance interrelations. After being presented with information about an object's travel time and speed, infants at the age of 18 months were able to correctly infer values of the distance dimension. However, correct inferences were made only under optimal (i.e., short) occlusion durations. Twenty-four-month-olds' distance inferences were more robust and not context-dependent in that way, indicating that the strength of infants' representations improves with age. In addition, it appeared that infants at the age of 12 months were not able to make correct inferences about an object's travel distance. Taken together, the results suggest that infants' ability to integrate information about time and speed and their ability to correctly infer the travel distance seems to develop within the first 18 months of life.

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1. Introduction

"Time and space are modes by which we think
and not conditions in which we live" (Einstein, 1879-1955).

In daily conversations adults easily and often use abstract terms like justice, numbers, or specifics about time. However, until now it remains unclear how such abstract entities (like time) are represented by the human mind. Given that temporal changes can only be imagined, time is considered to be an abstract entity while the same does not hold for e.g., space because spatial transformations can be perceived (Ornstein, 1969). One way how abstract entities are represented might be by the use of recycled sensory and motor representations that are developed by multiple interactions with the environment (Casasanto & Boroditsky, 2008). In fact, humans often use spatial language to express specifics about time (e.g., a long meeting or a short exam). One line of research was able to show that children's and adults' time representations are strongly influenced by irrelevant spatial information but the same does not apply vice versa (Casasanto & Boroditsky, 2008; Casasanto, Fotakopoulou, & Boroditsky, 2010). Thus, the same asymmetrical relation between time and space that can be found in linguistic metaphors (i.e., using spatial language to speak about time) seems to be existent in our *thinking* about time and space (i.e., time representations are interfered by irrelevant spatial information).

By contrast, another body of literature proposes that time, space, and numbers are represented by the same analog magnitude system that was demonstrated in animals (e.g., Meck & Church, 1983), children (e.g., Gallistel & Gelman, 2000), as well as infants (e.g., Brannon, Lutz, & Cordes, 2006; Brannon, Suanda, & Libertus, 2007; Lipton & Spelke, 2003; vanMarle & Wynn, 2006; Xu & Spelke, 2000). Generally and repeatedly it has been found that infants' time, space, and number discrimination is subject to Weber's law und thus, ratio-dependent. Moreover, neuroimaging studies demonstrated that the processing of time, space, and number share the same brain areas (Bueti & Walsh, 2009). Thus, this line of research indicates that in contrast to the above mentioned studies by Casasanto and colleagues (2008, 2010), time and space representations are rather symmetrically related to each other. In fact, this idea was expressed in Walsh's Theory of Magnitudes (ATOM, 2003). Binding of spatial and temporal representations has recently also been found in young infants, suggesting that a functional overlap does not rely on language and may be "part of our biological endowment" (Srinivasan & Carey, 2010, p. 237).

The question of how time and space are represented and how these concepts are developed has interested researchers for many years. However, as can be derived from the current and ongoing debate, this issue is far from being definitely answered. The present dissertation thesis provides data, by which the above stated general question can be newly addressed and continuity to our knowledge from research on children and adults can be aspired. By systematically investigating whether infants are aware of the interrelations that exist between time, speed, and distance dimensions, I aimed to answer the following questions: Are infants able to correctly infer values of one dimension of the time-speed-distance triad after being presented with information about the other two dimensions? In other words, do they have a rule-based understanding about time-speed-distance interrelations? How does this understanding develop? And are infants able to correctly integrate information about time and distance dimensions to discriminate between different speeds?

1.1 Children's understanding of time-speed-distance interrelations

In 1928, Albert Einstein asked Jean Piaget which of the two concepts develops earlier—the time or the speed concept. While in relativity theory both concepts are considered as basic concepts and are defined in terms of each other, the Newtonian mechanics define time as the basic concept and speed in terms of it (speed = distance/time). If Piaget would have found that both concepts are developed at the same time and neither one is derived from the other, Einstein would have likely claimed that assumptions of the relativity theory are intuitively present in humans. Piaget dedicated a large part of his seminal work on human's cognitive development to answering Einstein's original question. His investigations into children's knowledge of time-speed-distance interrelations revealed that children master these concepts and their interplay relatively late in their development at the ages of 9 to 10 years—that is, close to the Piagetian stage of concrete operations (Piaget, 1946a, 1946b, 1975). He reasoned that the speed concept is developed earlier (age 7 to 8 years) than the time concept (at the age of 12 to 14 years). Later work on children's knowledge about time, speed, and distance interrelations extended and refined Piaget's conclusions (Acredolo, Adams, & Schmid, 1984; Acredolo & Schmid, 1981, Siegler & Richards, 1979). For example, Siegler and Richards (1979) proposed that it is not until the ages of 16 to 17 years that adolescents fully understand the interrelations of the movement-related constituents.

Conclusions of Piaget (1946a, 1946b) and Siegler and Richards (1979) were challenged by studies of Wilkening (1981, 1982). He demonstrated that even at the early age of 5 years, children were able to correctly integrate information about time and speed to estimate values of distance. His investigations also showed that correct inferences about values of the time and speed dimensions awaits further development. Wilkening's results warrant several suggestions: First, children's intuitive knowledge about the physical interdependency between time, speed, and distance dimensions resembles the physical laws of classical mechanics. Second, children have a metric and conceptual understanding about time, speed, and distance dimensions. And third, children are aware of the interrelations between the movement-related dimensions—an assumption which sharply contrasts conclusions of former studies (Piaget, 1946a, 1946b, Siegler & Richards, 1979). However, the question regarding earliest signs of children's understanding about time-speed-distance interrelations remains unanswered. That is, the ontogenetic origin and developmental course of the sensitivity to time-speed-distance interrelations is still unclear.

1.2 Infants' sensitivity to spatiotemporal aspects of moving objects

The view about infants' perceptual world being "one great blooming, buzzing confusion" (James, 1890, p. 462), and Piaget's assumptions that the infant is devoid of any conceptual knowledge (Piaget, 1952) have been repeatedly called into question by findings of various infant studies (e.g., Baillargeon, 1987a; Baillargeon, Spelke, & Wasserman, 1985; Kellman & Spelke, 1983; Leslie, 1984; Leslie & Keeble, 1987). In fact, by the use of innovative methods (e.g., looking-time measurements or eye tracking technology) the image of the infant has changed from a human being that is helpless and underdeveloped to one that is perceptually, cognitively, and socially sophisticated and competent right from the start (see Rauh, 2002). It is now a well-accepted finding that even shortly after birth, infants are aware of several physical laws that govern object's movements. For example, infants are sensitive to spatiotemporal continuity, inertia, and the dynamics of an object's movement (Gredebäck & von Hofsten, 2004; Spelke, Kestenbaum, Simons, & Wein, 1995; von Hofsten, Feng, & Spelke, 2000; von Hofsten, Visthon, Spelke, Feng, & Rosander, 1998). Indeed, infants expect objects to move continuously in time and space (Johnson et al., 2003; Spelke et al., 1995; Wilcox & Schweinle, 2003). If the basic physical law of spatiotemporal continuity is violated, infants seem to draw conclusions accordingly (see Spelke et al., 1995). Furthermore, infants expect forces that affected visible object's movements prior to occlusion to continue during the occlusion period and thus, expect linear and inert object movements (von Hofsten et al., 2000; von Hofsten et al., 1998). Finally, infants were found to be aware of the spatiotemporal dynamics of an object's movement and anticipated the appearances of temporarily occluded objects correctly (Gredebäck & von Hofsten, 2004; von Hofsten, Kochukhova, & Rosander, 2007). However, whether infants are sensitive to another important physical law that governs objects' movements, namely time-speed-distance interrelations, is until now virtually unexplored. Investigations about infants' rule-based understanding of time-speed-distance interrelations and about infants' ability to infer values of one dimension after being presented with values of other two dimensions have been sparse.

Combining both lines of research—infants' sensitivity to spatiotemporal properties of movements and children's intuitive knowledge about time-speed-distance interrelations—reveals a gap that the present dissertation thesis intended to close. In particular, the present works attempted to answer the question of whether infants are sensitive to time-speed-distance interrelations. Analogous to previous studies (Wilkening, 1981, 1982), infants were confronted with values of two dimensions and their ability to infer values of the third dimension was measured. That is, the focus of the present investigations was on infants' rule-based understanding about time-speed-distance interrelations.

1.3 Goals of the present studies

Given that time-speed-distance interrelations are inherent in every natural movement and that from an early age on infants are confronted with moving objects, the investigation of infants' sensitivity to the interdependency between time, speed, and distance dimensions seems timely. Within the following experiments, I tried to answer the questions of a) whether infants are able to correctly integrate time and distance information in order to discriminate different speeds (Manuscript 1: Möhring, Libertus, & Bertin); and b) when infants are able to infer correct values of the distance dimension after being presented with values of the time and speed dimension (Manuscript 2: Möhring, Cacchione, & Bertin; Manuscript 3: Möhring & Bertin). By the use of a multi-method approach (looking-time measures, action-based tasks, and eye-tracking technologies), it was possible to gain new insights into infants' and toddler's sensitivity to time-speed-distance interrelations.

The first study by Möhring, Libertus, and Bertin (*Journal of Experimental Child Psychology,* in press) investigated whether 6- and 10-month-old infants' ability to discriminate between different speeds is subject to Weber's law. Given that speed can be defined as the distance traveled within a certain period of time, and that both time and space discrimination are ratio-dependent (Brannon et al., 2006; Brannon et al., 2007), it is plausible that speed discrimination is likewise subject to Weber's law. However, previous studies found contradictory evidence for this assumption (Ahmed, Lewis, Ellemberg, & Maurer, 2005; Dannemiller & Freedland, 1991). Within three experiments using the habituation-dishabituation paradigm, we were able to show that 6-month-old infants' ability to discriminate different speeds was ratio-dependent. In addition, infants' ability increased in precision by the time infants were

10 months old—which parallels infants' time discrimination behavior (Brannon et al., 2007). Therefore, our results add to the growing body of literature that indicates that time, space, number, and also speed representations are processed by a common underlying mechanism and/or comparison process.

Within the second set of studies, Möhring, Cacchione, and Bertin (*Infant Behavior and Development,* in press) examined whether 18- and 24-month-old infants are able to infer values of the distance dimension after being presented with information about time and speed. Using an action-based task, we were able to demonstrate that even at the early age of 18 months, infants were able to correctly infer an object's travel distance. However, infants' inferences were highly dependent on the occlusion duration of the moving object. That is, only when occlusion duration was reduced within a second experiment, were infants able to correctly infer the moving object's travel distance. By contrast, occlusion duration was not a crucial factor for 24-month-old infants' correct distance inferences, showing that the strength of infants' representations improves with age. Therefore, our findings indicate that the origin of infants' sensitivity to time-speed-distance interrelations lies at least around the age of 18 months. In addition, these findings add to research about the general nature of infants' representations (e.g., Berthier et al., 2001; Keen, Carrico, Sylvia, & Berthier, 2003; Munakata, 2001; Munakata, McClelland, Johnson, & Siegler, 1997; Shinskey & Munakata, 2005).

Building upon the results discussed in the second manuscript, Möhring and Bertin (submitted) tested in a third set of investigations whether infants younger than 18 months were able to infer an object's travel distance. Analogous to former studies (Wilkening, 1981, 1982), infants were presented with values of the time and speed dimension and their ability to infer values of the distance dimension were measured. Infants' exact eye movements were measured by the use of the eye-tracking technology. Our findings indicate that 12-month-old infants were not able to infer values of the travel distance while 18-month-olds were able to do so. This result indicates important age-dependent changes in the ability to infer distance values. Several hypotheses are discussed to explain this developmental pattern (i.e., self-locomotion; see Newcombe & Huttenlocher, 2000).

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Speed discrimination in 6- and 10-month-old infants follows Weber's law

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2. Speed discrimination in 6- and 10-month-old infants follows Weber's law

2.1 Abstract

The authors investigated speed discrimination in 6- and 10-month-old infants using a habituation paradigm showing infants events of a ball rolling at different speeds. Six-month-olds looked longer at novel speeds that differed by a 1:2 ratio than at the familiar ones but showed no difference in looking time to speeds that differed by a 2:3 ratio. In contrast, 10-month-olds succeeded at discriminating a 2:3 ratio. For both age groups, discrimination was modulated by the ratio between novel and familiar speeds suggesting that speed discrimination is subject to Weber's law. These findings show striking parallels to previous results in infants' discrimination of duration, size, and number and suggest a shared system for processing different magnitudes.

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Keywords: Speed Discrimination, Weber's law, Infancy

2.2 Introduction

We are often faced with situations in which we have to judge the speed of an object and make decisions based on these judgments. For example, we need to consider the speed of an approaching car before we cross the street or adjust our movements with respect to the speed of a ball that somebody throws at us in order to catch it. Our daily experiences help us to sharpen our judgments to avoid dangerous or unpleasant outcomes. However, it is not clear whether many years of active experience are necessary to make such judgments. Hence, in the present study we investigate whether infants can discriminate between different speeds of objects and how this ability changes over the first year of life.

Prompted by Albert Einstein's question how children acquire the concepts of time and speed, Jean Piaget published two groundbreaking books on children's conceptions of time and of movement and speed (Piaget, 1946a/1969, 1946b/1970). In his view, children take many years to acquire these concepts and do not attain a full understanding until they reach the concrete operational stage around the age of nine to ten years. Initially during the preoperational stage around four years of age, children judge time, distance, and speed solely by the spatial stopping points. To them, "speed is overtaking" (Piaget, 1970, p. 293). As children get older, they are thought to start considering other factors such as the starting points, distance, and time.

Further experimental support for this protracted and successive development of the three concepts has come from work by Siegler and Richards (1979). In their study, children and adults were shown two parallel train tracks. The trains could vary in their starting and stopping points, in the distances and durations travelled, and their speeds. After watching certain combinations of train-travelling events, participants were asked to judge which train went further, longer in time, or faster. In line with Piaget's descriptions, 5-year-old children equated time, distance, and speed with the stopping points of the trains and older children acquired the concept of time last. However, children seemed to master all three concepts even later than Piaget had observed and the transition period before then was characterized by various stages of confusion of the relationships between time, distance, and speed.

In contrast, Wilkening (1981, 1982) showed evidence that children at the age of 5 years have an intuitive knowledge about time, speed, and distance interrelations. In one variation of his task, children were requested to infer how far an animal would escape from a barking dog while the quickness of the animal (speed) and the duration of the dog's barking (time) were varied. He found that children from the age of 5 years were able to correctly infer values of distance, illustrating that even at this early age children integrated information correctly. However, children's correct inferences about speed and time awaited further development. Thus, Wilkening concluded that children have an implicit knowledge about time, speed, and distance interrelations but that the distance concept develops before the concepts of speed and time. Moreover, Levin (1979) showed that it is not just time and speed that are often confused, but that children also confuse time and other quantifiable domains such as brightness suggesting that children have difficulty separating conflicting quantifiable information in general and not just with respect to the related concepts of time, distance, and speed.

As reviewed above, children from an early age seem to have an intuitive knowledge about time, speed, and distance interrelations. Therefore, it is not surprising that previous research demonstrates that even infants do in fact understand a lot about objects and the principles that govern objects' behavior in time and space. For example, seminal work by Spelke, Kestenbaum, Simons, and Wein (1995) showed that 5-month-old infants expect an object to exist continuously in time and space, suggesting that sensitivity to movement and speed is present early in development. It has also been shown that infants' visual tracking behavior is highly sensitive to variation in object speed (Mareschal, Harris, & Plunkett, 1997) and that they use speed information to individuate objects (Wilcox & Schweinle, 2003). Furthermore, Baillargeon, Spelke, and Wasserman (1985) showed that 5-month-old infants understand that objects continue to exist even when hidden from view and that solid objects cannot move through other solid objects. Finally, Lewkowicz (1992) showed that 4- and 8-month-old infants' ability to match auditory and visual information is disrupted when speed or rate of object movement vary providing indirect evidence that infants are sensitive to speed.

Moreover, previous studies with infants have shown that they possess remarkable discrimination abilities for time and distance. For example, previous behavioral work has shown that infants are capable of discriminating between durations in the seconds range and that this ability increases with age (Brannon, Suanda, & Libertus, 2007; vanMarle & Wynn, 2006). In these studies, infants were first habituated to an event of a given duration (e.g., a cow mooing for 1.5 seconds) and then tested with events of the familiar duration and a novel duration (e.g., a cow mooing for 3 seconds). Six-month-old infants consistently looked longer at the novel duration event if the durations differed by a 1:2 ratio, but failed at a 2:3 ratio. However, by ten months of age infants succeeded at discriminating durations that differed by a 2:3 ratio (e.g., 2 vs. 3 seconds) but failed at a 3:4 ratio suggesting that infants' acuity in discriminating durations increases over the first year of life (Brannon et al., 2007). Importantly, infants' success in discriminating between the different durations adhered to Weber's law. That is, discriminability was determined by the ratio and not the absolute difference between the values, thus, supporting the notion that duration discrimination in infancy parallels ratio-dependent duration discrimination behavior previously found in non-human animals and adults (e.g., Gibbon, 1977; Wearden, 1992).

Convergent evidence for ratio dependence in infants' duration discrimination comes from a set of electrophysiological studies (Brannon, Libertus, Meck, & Woldorff, 2008; Brannon, Roussel, Meck, & Woldorff, 2004). Here, 10-month-old infants were presented with a stream of tones in which the intertone intervals differed in duration. Most tones were separated by a fixed duration (standards) but occasionally this duration was varied (deviants). The difference in the event-related potentials (ERPs) between standard and deviant durations was found to be modulated by the ratio between durations rather than the absolute difference. Thus, these findings provide additional electrophysiological evidence that Weber's law holds when infants discriminate different durations.

Less work has been done on infants' ability to discriminate lengths, sizes, or continuous extent, but the extant findings parallel the results obtained in the time domain. Using a habituation paradigm, Brannon, Lutz, and Cordes (2006) showed that 6-month-old infants are able to discriminate between different sizes of a single Elmo face as long as there is at least a twofold change in size. In addition, infants' reaching behavior and attention to objects is modulated by the distance between themselves and the objects suggesting that they are able to discriminate between different distances at least when they are behaviorally relevant (Field, 1976).

Additional support for the notion that Weber's law governs time, length, and also number discrimination comes from a recent behavioral study on children and adults (Droit-Volet, Clement, & Fayol, 2008). Using a bisection procedure in which children and adults had to classify intermediate values as either being more similar to a short/few anchor or a long/many anchor, the authors showed that judgments in all three domains were modulated by the ratio between the intermediate value and the anchors. Importantly, when lengths were presented sequentially (i.e., as parts of a line that needed to be added to judge the total length), the bisection functions for time and length were indiscriminable even for children as young as five years of age. Given that in physical sciences or engineering, distance can be seen as equivalent to “unit of length” or “physical length” (Pople, 1987), it is reasonable to argue that distance discrimination is supported by analog magnitudes in the same way as length discrimination is (see also Spelke, Lee, & Izard, 2009). Furthermore, 3-year-old children were aware of the relation between length and distance in an action-based task (Miller & Baillargeon, 1990).

Since speed can be expressed as the ratio between distance and travel time and discrimination in both domains seems to be governed by Weber’s law, it is natural to assume that speed discrimination should also be ratio dependent. However, with regards to speed discrimination in infancy and childhood previous works suggests a differentiation between discrimination of slow and fast speeds (e.g., Ahmed, Lewis, Ellemberg, & Maurer, 2005; Dannemiller & Freedland, 1991). In particular, Dannemiller and Freedland (1991) presented 5-month-old infants with two bars moving at different speeds and measured infants’ looking behavior to these displays. Infants showed significant preferences for the faster moving bars at all speeds but more so when the bars moved slowly than when they were moving rapidly. The approximate Weber fraction – the difference between the two speeds divided by the larger of the two – was approximately 0.35 for speeds of 3.3°/s and 5°/s and 0.67 for a speed of 10°/s suggesting a finer discrimination ability for slower than for faster speeds. In contrast, Ahmed and colleagues (2005) found that 5-year-olds and adults were better at discriminating speeds of moving bars at faster speeds (6°/s) as compared to slower speeds (1.5°/s). Thus, neither study provides support for the notion of Weber's law but importantly these previous studies provide mixed evidence as to whether it is easier to discriminate slow or fast speeds.

The goals of the present study were twofold: First, we wanted to investigate whether infants' ability to discriminate different speeds was modulated by the ratio between the speeds as predicted by Weber's law or whether there are differences in discrimination of slow and fast speeds. Second, we examined the developmental trajectory of speed discrimination between 6 and 10 months of age. Previous findings in the domain of duration and continuous extent discrimination suggest an increase in acuity over the first year of life. Thus, we hypothesized that speed discrimination acuity will also increase between 6 and 10 months of age. To address these issues, we used a habituation paradigm in which different groups of 6- and 10-month-old infants were first habituated to a ball rolling across the screen at a given speed and then tested with the familiar and a novel speed. We hypothesized that if infants are able to discriminate between the familiar and novel speeds, they will spend more time looking at the novel speed.

2.3 Experiment 1

2.3.1 Method

Participants. Twenty-four healthy, full-term 6-month-old infants (mean age = 189.92 days, *SD* = 10.50 days; 13 males) participated in this experiment. One additional infant was tested but excluded from the final sample due to parental interference. All infants were recruited from a pool of families who had volunteered to take part in studies of child development. Infants in this and the following experiments were predominantly Caucasian and from middle-class backgrounds. Parents filled out a consent form prior to the start of the study and infants received a toy for their participation.

Stimuli. Stimuli were colorful computer-animated events created using Adobe Flash CS3 Professional (Adobe Systems Inc.). At the beginning of each event, infants saw a stationary red ball for one second. It was located at the left side of the screen. Afterwards the ball moved with constant speed along a straight horizontal trajectory from left to right. After the ball's movement stopped, the ball rested at its final location for three seconds. Each movement of the ball was accompanied by the same continuous rolling sound, which was presented only if the ball moved. While times and distances of the ball's movement were varied between the habituation trials, speed was always held equal during habituation with a particular absolute value depending on the habituation condition (see Table 1).

Immediately following habituation (e.g., to a ball moving 5 cm/s), infants were presented with test trials in which the ball moved alternately with the familiar (e.g., 5 cm/s) or a novel speed (e.g., 10 cm/s). Time and distance values were different compared to values of these dimensions during habituation. All events (habituation and test trials) were presented in loops with a blank screen of one second between repetitions.

Apparatus and Procedure. The stimuli were presented on a 30-inch computer monitor. Infants sat on the caregiver's lap in a dimmed room approximately 60 cm in front of the computer screen. Dark brown curtains hung from the ceiling to the floor preventing infants from visual distraction. A camera mounted above the computer screen monitored and recorded infants' looking direction and duration.

An infant-controlled habituation procedure was used in this and the following experiments. Each trial began with an attention getter (rapidly alternating green and purple geometric shapes) directing the infant's attention to the left side of the computer screen—the location where the red ball would appear. Once the infant's attention was secured, the experimenter started the first habituation trial by pressing a computer key. Recording of the infants' looking time began as soon as the trial started. Each habituation trial remained on the screen until the infant looked away for 2 consecutive seconds or until 60 seconds had elapsed. Habituation trials continued until the mean looking duration during three consecutive trials for each infant was less than or equal to half of the mean looking duration during the first three trials for the same infant or until the infant had gone through a maximum of 15 habituation trials.

We used two speed pairs in which the absolute values both differed by a 1:2 ratio (absolute value groups: 5 cm/s and 10 cm/s vs. 2.5 cm/s and 5 cm/s). Half of the infants were habituated to one speed in the first speed pair (i.e., 5 cm/s (approx. 4.8°/s) or 10 cm/s (approx. 9.5°/s)) and tested with both speeds in this pair, the other half of the infants were habituated to one speed in the second speed pair (i.e., 2.5 cm/s (approx. 2.4°/s) or 5 cm/s) and tested with both speeds in that pair. Consequently, for each speed pair (e.g., 5 cm/s and 10 cm/s), half of the infants were habituated to the slower speed (e.g., 5 cm/s) and the other half were habituated to the faster speed (e.g., 10 cm/s). For each speed (2.5 cm/s, 5 cm/s, and 10 cm/s), four different habituation trials were created and presented in a randomized order.

All infants were tested with six test trials, presented in an alternating order between familiar and novel test trials. Order of familiar and novel test trials was counterbalanced between the infants. Analogous to the habituation, test trials remained on the screen until the infant looked away for 2 consecutive seconds or until 60 seconds had elapsed.

The following is an example demonstrating the habituation and test procedure for an imaginary participant. The infant is presented with a speed of 5 cm/s during the habituation trials. That is, the infant is presented with the ball moving a distance of 7.5 cm in 1.5 s in the first habituation trial. During the second habituation trial, the ball moves a distance of 12.5 cm in 2.5

s. During the third habituation trial, the ball moves a distance of 10 cm in 2 s. During the fourth habituation trial, the ball moves a distance of 5 cm in 1 s. Thus, each value in distance and time constitutes a speed of 5 cm/s. After the infant reaches the habituation criterion, he/she is presented with the familiar test trial (F), in which the ball moves a distance of 8.75 cm in 1.75 s (consistent with a speed of 5 cm/s). During the novel test trial (N), the ball moves a distance of 12.5 cm in 1.25 s (consistent with a speed of 10 cm/s). The familiar and novel test trials are repeated for three times in an alternating order (FNFNFN or NFNFNF).

The test trial performance of twelve randomly chosen infants was reassessed by a second naïve rater to calculate interrater reliability. The average Pearson correlation between the two observers was .98.

2.3.2 Results

Habituation phase. Twenty-two out of 24 infants met the habituation criterion[1]. The mean number of habituation trials was 7.50 trials (*SD* = 2.49). To assess whether infants' habituation was influenced by any between-subjects factors, an analysis of variance with habituation (first vs. last three habituation trials) as within-subjects variable and gender, habituation condition (slower vs. faster speed), and absolute value (2.5 and 5 cm/s vs. 5 and 10 cm/s) as between-subjects variables was computed. The analysis revealed a significant main effect of habituation, $F(1, 16) = 67.28$, $p < .001$, $\eta_G^2 = .59$, but no other significant effects. Thus, while infants reliable decreased their looking from the first to the last three habituation trials, there is no evidence suggesting that their habituation was influenced by habituation condition, the absolute value of the speed during habituation, or gender.

Test phase. Despite the fact that all infants were habituated to a fixed speed, due to the variation in the number of habituation trials between infants, the average time and distance of the events across habituation differed between individuals and was not always the exact average that was used for the familiar test trials (see Table 1). In a preliminary analysis, we assessed whether this variation had any impact on infants' looking times in the test phase. An analysis of variance with test trial type (familiar vs. novel test trial) as within-subjects variable and the difference between the average habituation distance and the distance in the familiar test trials as covariate revealed neither a significant interaction nor a significant main effect of differences in distance, indicating that this variation did not influence infants' looking behavior during the test phase. Given that distance and time in this experimental design are directly related to each other, differences in average time of the habituation events did not influence infants' looking behavior during test either. Figure 1 refers to the mean looking time in seconds for the first three and last three habituation trials as well as infants' looking time to the familiar and novel test trials.

In general, 6-month-old infants were able to discriminate between speeds that differed by a 1:2 ratio. A 2 × 2 × 2 × 2 mixed-factor analysis of variance (ANOVA) with the between-subjects factors of gender, habituation condition (slower vs. faster speed), and absolute value (2.5 and 5 cm/s vs. 5 and 10 cm/s) and within-subjects factor of test trial type (familiar vs. novel test trial) revealed a significant main effect of trial type, $F(1, 16) = 5.52$, $p < .05$, $\eta_G^2 = .11$. That is, infants looked significantly longer at the novel ($M = 15.52$ s, $SE = 1.62$ s) than at the familiar test trial ($M = 10.87$ s, $SE = 1.45$ s). There were no other significant effects, all Fs < 1.67, ps > .21[2] (refer to Table 2 for infants' looking times to familiar and novel test trials separately for each habituation condition and absolute value group). Moreover, 19 out of 24 infants had a greater average looking time to the novel test trials as compared to the familiar test trials (Binomial, $p < .01$).

Furthermore, infants showed a dishabituation effect to the first novel test trial (cf. Hespos, Grossman, & Saylor, 2010), i.e., they looked longer at the first novel test trial (M = 19.04 s, SE = 2.84 s) than toward the last habituation trial (M = 10.86 s, SE = 1.48 s), $t(23) = -2.79$, $p < .05$. In contrast, they looked about equally toward the last habituation and the first familiar test trial (M = 10.37 s, SE = 1.07 s), $t(23) = .29$, $p > .05$.

2.3.3 Discussion

The results of Experiment 1 suggest that 6-month-old infants are capable of discriminating speeds that differ by a 1:2 ratio. Importantly, this ability seems to be solely determined by the ratio between the values and not the absolute difference or the speed they were habituated to. In addition, slight differences in the average distance or time between the events during habituation and those used in the familiar test trials did not affect infants' looking behavior during the test phase. Overall, our results show remarkable similarities to findings regarding infants' discriminative abilities for duration, size, and number (Brannon et al., 2006; Brannon et al., 2007; vanMarle & Wynn, 2006). Given previous reports of 6-month-olds' failure to differentiate durations or sizes that differed by a 2:3 ratio, we examined this age groups' ability to discriminate speeds that differ by this ratio in the next experiment.

2.4 Experiment 2

2.4.1 Method

Participants. Twenty-four healthy, full-term 6-month-old infants (mean age = 187.33 days, *SD* = 9.84 days; 12 males) participated in the present experiment. One additional infant was tested but excluded from the sample due to fussiness. All infants were recruited in the same manner as in Experiment 1.

Stimuli, apparatus, and procedure. Stimuli, apparatus, and procedure were analogous to Experiment 1 aside from the following exceptions. Half of the infants were tested with speeds of 5 cm/s and 7.5 cm/s (approx. 7.1°/s) and half with speeds of 6.66 cm/s (approx. 6.3°/s) and 10 cm/s (both consistent with a ratio of 2:3). In each speed pair (e.g., 5 cm/s and 7.5 cm/s), half of the infants were habituated to the slower speed (e.g., 5 cm/s) and half to the faster speed (e.g., 7.5 cm/s). For each speed (5 cm/s, 6.66 cm/s, 7.5 cm/s, and 10 cm/s), four different habituation trials were created and presented in a randomized order. Values of distance and time dimensions were varied (see Table 3; for speeds of 5 and 10 cm/s, values of distance and time were identical to Experiment 1).

Again, the test performance of twelve randomly chosen participants was reassessed by a second naïve rater to calculate interrater reliability. The average Pearson correlation between the two observers was .97.

2.4.2 Results and Discussion

Habituation phase. All infants met the habituation criterion. The mean number of habituation trials was 7.33 trials (*SD* = 2.26). To assess whether infants' habituation was influenced by any between-subjects factors, an analysis of variance with habituation (first vs. last three habituation trials) as within-subjects variable and gender, habituation condition (slower vs. faster speed), and absolute value (5 and 7.5 cm/s vs. 6.66 and 10 cm/s) as between-subjects variables was computed. The analysis revealed a significant main effect of habituation, $F(1, 16) = 68.18$, $p < .001$, $\eta_G^2 = .42$, but no other significant effects. Thus, while infants reliable decreased their looking from the first to the last three habituation trials, there is no evidence suggesting that their habituation was influenced by any between-subjects factors such as habituation condition, absolute value of the speed used during habituation, or gender.

Test phase. Again, despite the fact that all infants were habituated to a fixed speed, the variation in the number of habituation trials between infants led to differences in the average time and distance of the events that each individual was habituated to. These actual averages were not always the exact average that was used for the familiar test trials (see Table 3). Thus, in a preliminary analysis we assessed whether these variations had any impact on infants' looking times in the test phase. An analysis of variance with test trial type (familiar vs. novel test trial) as within-subjects variable and the difference between the average habituation distance and the distance in the familiar test trials as covariate revealed neither a significant interaction nor a significant main effect of differences in distance, indicating that this variation did not influence infants' looking behavior during the test phase. Figure 2 refers to the mean looking time in seconds for the first three and last three habituation trials as well as looking time to the familiar and novel test trials.

In general, 6-month-old infants were not able to discriminate between speeds that differed by a 2:3 ratio. A 2 × 2 × 2 × 2 mixed-factor analysis of variance (ANOVA) with the between-subjects factors of gender, habituation condition (slower vs. faster speed), and absolute value (5 and 7.5 cm/s vs. 6.66 and 10 cm/s) and within-subjects factor of test trial type (familiar vs. novel test trial) revealed no significant effects, all *F*s < 2.38, *p*s > .14. Infants looked equally long at the novel (*M* = 10.39 s, *SE* = 1.33 s) and the familiar test trial (*M* = 9.40 s, *SE* = 1.34 s). Moreover, only 14 out of 24 infants had a greater average looking time to the novel test trials as compared to the familiar test trials (Binomial, $p > .05$).

Furthermore, infants did neither recover their looking time from the last habituation trial (*M* = 10.50 s, *SE* = 2.02 s) to the first novel test trial (*M* = 13.20 s, *SE* = 2.68 s), $t(23) = -.93$, $p > .05$, nor to the first familiar test trial (*M* = 9.31 s, *SE* = 1.51 s), $t(23) = 0.65$, $p > .05$.

Most importantly, comparing 6-month-olds' test performance during Experiments 1 and 2 in a 2 × 2 ANOVA with the between-subjects factor ratio (1:2 vs. 2:3) and within-subjects factor of test trial type (familiar vs. novel test trial) revealed a significant effect of test trial type, $F(1, 46) = 7.05$, $p < .05$, $\eta_G^2 = .04$, and a marginally significant interaction between ratio and test trial type, $F(1, 46) = 2.96$, $p < .1$, $\eta_G^2 = .02$. With regards to the means, this interaction suggests that 6-month-old infants were able to discriminate a novel from a familiar speed when these differed by a 1:2 ratio, while same-aged infants failed to do likewise when tested with speeds differing by a ratio of 2:3. The inability to discriminate speeds that differ by a 2:3 ratio at 6 months of age is consistent with findings about infants' duration, size, and number discrimination (Brannon et al., 2006; Brannon et al., 2007; Lipton & Spelke, 2003; vanMarle & Wynn, 2006). However, since previous results show that infants' discrimination increases in precision with age (Brannon et al., 2007), we tested whether 10-month-olds are capable of performing a discrimination of speeds that differ by a 2:3 ratio.

2.5 Experiment 3

2.5.1 Method

Participants. Twenty-four healthy, full-term 10-month-old infants (mean age = 308.79 days, *SD* = 8.20 days; 13 males) participated in the present experiment. Neither of these infants did participate in Experiment 1 or 2. Three additional infants were tested but excluded from the sample due to fussiness (n = 2) and experimenter error (n = 1).

Stimuli, apparatus and procedure. Stimuli, apparatus, and procedure were analogous to Experiment 2 (see also Table 3 for more details). Again, half of the infants were randomly chosen and their test performance was reassessed by a second naïve rater to calculate interrater reliability. The average Pearson correlation between the two observers was .99.

2.5.2 Results and Discussion

Habituation phase. All infants met the habituation criterion. The mean number of habituation trials was 7.83 trials (*SD* = 2.01). To assess whether infants' habituation was influenced by any between-subjects factors, an analysis of variance with habituation (first vs. last three habituation trials) as within-subjects variable and gender, habituation condition (slower vs. faster speed), and absolute value (5 and 7.5 cm/s vs. 6.66 and 10 cm/s) as between-subjects variables was computed. The analysis revealed a significant main effect of habituation, $F(1, 16) = 81.20$, $p < .001$, $\eta_G^2 = .49$, but no other significant effects. Thus, while infants reliable decreased their looking from the first to the last three habituation trials, there is no evidence suggesting that their habituation was influenced by any between-subjects factor such as habituation condition, absolute value of the speed used during habituation, or gender.

Test phase. Again, despite the fact that all infants were habituated to a fixed speed, the variation in the number of habituation trials between infants led to differences in the average time and distance of the events that each individual was habituated to. These actual averages were not always the exact average that was used for the familiar test trials (see Table 3). Thus, in a preliminary analysis we assessed whether these variations had any impact on infants' looking times in the test phase. An analysis of variance with test trial type (familiar vs. novel test trial) as within-subjects variable and the difference between the average habituation distance and the distance in the familiar test trials as covariate revealed neither a significant interaction nor a significant main effect of differences in distance, indicating that this variation did not influence infants' looking behavior during the test phase. Figure 3 refers to the mean looking time in seconds for the first three and last three habituation trials as well as infants' looking time to the familiar and novel test trials.

In general, 10-month-old infants were able to discriminate between speeds that differed by a 2:3 ratio. A 2 × 2 × 2 × 2 mixed-factor analysis of variance (ANOVA) with the between-subjects factors of gender, habituation condition (slower vs. faster speed), and absolute value (5 and 7.5 cm/s vs. 6.66 and 10 cm/s) and within-subjects factor of test trial type (familiar vs. novel test trial) revealed a significant main effect of test trial type, $F(1, 16) = 9.94$, $p < .01$, $\eta_G^2 = .20$. That is, infants looked significantly longer at the novel ($M = 10.03$ s, $SE = 1.06$ s) than the familiar test trial ($M = 6.61$ s, $SE = 0.56$ s). There were no further significant effects, all Fs < 1.19, all ps > .29. Moreover, 18 out of 24 infants had a greater average looking time to the novel test trials as compared to the familiar test trials (Binomial, $p < .05$).

Furthermore, infants showed a dishabituation effect to the first novel test trial, i.e., they looked longer at the first novel test ($M = 11.71$ s, $SE = 2.65$ s) than toward the last habituation trial (M = 6.89 s, SE = 1.67 s), $t(23) = -2.52$, $p < .05$. In contrast, they looked about equally long toward the last habituation and the first familiar test trial (M = 7.64 s, SE = 1.17 s), $t(23) = -0.41$, $p > .05$.

However, comparing 6 and 10-month-old infants' performance in an ANOVA with the between-subjects factor of age (6 vs. 10 months) and the within-subjects factor of test trial type (familiar vs. novel test trial) revealed only a significant main effect for test trial type, $F(1, 46) = 6.25$, $p < .05$, $\eta_G^2 = .04$, but no other significant effects (all ps > .05). Although this analysis yielded a non-reliable difference in infants' response, the parametric and nonparametric analyses for the two age groups suggest that 10-month-olds were able to discriminate speeds differing by a 2:3 ratio, while 6-month-olds failed to do so.

2.6 General Discussion

The findings of the three experiments presented in this paper show that infants as young as 6 months of age are capable of discriminating speeds of objects moving on a screen and that their acuity to perform such a discrimination increases between 6 and 10 months of age. While 6-month-olds fail to discriminate speeds that differ by a 2:3 ratio, 10-month-olds succeed at this task. Most importantly, at both ages infants' speed discrimination is governed by Weber's law. That is, the ratio between the speeds determines discriminability and not the absolute difference.

Our findings show remarkable parallels with infants' discrimination thresholds for duration, size, and number. In all four domains, 6-month-old infants are capable of discriminating values that differ by a 1:2 ratio and fail at a 2:3 ratio (Brannon et al., 2006; Brannon et al., 2007; Libertus & Brannon, 2010; Lipton & Spelke, 2003; vanMarle & Wynn, 2006; Xu & Spelke, 2000). Similarly, infants' discrimination abilities for duration, number, and -

as evidenced in the current studies - speed seem to improve between the age of 6 and 10 months, in that older infants can also discriminate values that differ by a 2:3 ratio (Brannon et al., 2007; Libertus & Brannon, 2010; Lipton & Spelke, 2003). Since speed is defined in terms of duration and distance, it is not surprising that speed discrimination is subject to Weber's law in the same way as time and space discriminations are. What is surprising, however, is the fact that infants show the same threshold of sensitivity at a 1:2 ratio in all four domains. Contrary to previous research (Bahrick, Lickliter, Castellanos, & Vaillant-Molina, 2010; Bahrick, Flom, & Lickliter, 2002; Jordan, Suanda, & Brannon, 2008), it seems as if the intersensory redundancy of visual and auditory information present in our stimuli did not enhance infants' discrimination abilities.

These parallels support the notion of a common format and/or comparison process underlying the representations of time, number, and space and additionally speed (Cantlon, Platt, & Brannon, 2009; Meck & Church, 1983; Walsh, 2003; Droit-Volet, 2010). In fact, it has been suggested that this holds for all quantifiable dimensions including for instance brightness, weight, and loudness, and that discrimination in all dimensions is thus subject to Weber's law (Bueti & Walsh, 2009; Cantlon et al., 2009; Gallistel & Gelman, 2000). Recent work with infants suggests that the mapping of number and time onto space is already present in infancy and thus does not rely on language (de Hevia & Spelke, 2010; Lourenco & Longo, 2010; Srinivasan & Carey, 2010).

Current evidence from neuropsychological and neuroimaging studies suggests that parietal cortex, in particular inferior parietal regions, may be the locus of such domain-general representations and/or computations (see Bueti & Walsh, 2009; Cantlon et al., 2009; Cohen Kadosh, Lammertyn, & Izard, 2008; Walsh, 2003, for reviews). For example, patients with hemispatial neglect resulting from a lesion to the parietal cortex have been found to misjudge both the midpoint of a physical line as well as the midpoint between two numerical values suggesting a close link between the representations of number and space (Zorzi, Priftis, & Umilta, 2002). Similarly, a patient with left unilateral neglect was found to exhibit signs of misjudging the velocity of a left-moving object suggesting that speed judgments may also be affected by lesions to the parietal lobe (Geminiani, Corazzini, Stucchi, & Gindri, 2004). Thus, our findings fit with previous results in that the speed of an object may be represented in a similar format as other magnitudes and/or that speed discrimination shares a common comparison process with other magnitudes.

The present findings contradict previous results that found differences between 5-month-old infants' abilities to discriminate slower and faster speeds (Dannemiller & Freedland, 1991). The authors found that infants showed significant preferences for the faster moving bars at all speeds but more so when the bars moved slowly than when they were moving rapidly. Several factors might account for these differences: First, Dannemiller and Freedland used a preferential looking paradigm in which both speeds were presented simultaneously assuming that infants would always prefer to look to the faster speed. However, it is conceivable that infants' preference for the faster speed is determined by the absolute value of the speed irrespective of their ability to discriminate them. For example, infants might have a particular preference for faster speeds up to about 5°/s, but do not exhibit such a strong preference once speeds are faster than that. Second, in Dannemiller and Freedland's study the temporal frequency of the moving bars was correlated with the speed at which they moved. Even though the authors tried to rule out this factor as a basis for discrimination, it is still conceivable that infants were using it or other perceptual cues rather than speed. In contrast, in our study no such cues were available: Infants were habituated to different events in which a ball moved at a fixed speed, but distance and duration varied rendering these variables invalid as a basis for discrimination. Furthermore, we also employed completely novel events for the familiar test trials to ensure that both novel and familiar test trials had not been viewed before. Finally, if infants had an inherent bias to look longer to the faster moving object, we would expect to see an interaction between the habituation condition (slower or faster speed) and their novelty preference. However, this was not the case in our data suggesting that infants' ability to discriminate between different speeds is not modulated by the absolute value of the speed.

The present findings also contradict previous findings by Ahmed and colleagues (2005). These authors found that 5-year-olds and adults were better at discriminating speeds of moving bars at faster speeds (6°/s) as compared to slower speeds (1.5°/s). Several factors might account for these differences: First, the temporal frequency of the moving bars was again correlated with the speed at which they moved similar to Dannemiller and Freedland's stimuli (1991). Thus, it is again conceivable that participants were using it or other perceptual cues rather than speed to make their discriminations. Second, Ahmed and colleagues used a staircase procedure to estimate the difference needed to discriminate a given speed from a slow or fast reference speed. While the number of trials to reach threshold did not differ much between children and adults, there was considerable variability between participants. Unfortunately, no data is available to determine whether the number trials to reach threshold differed between slow and fast reference speeds. In our study, no differences in number of habituation trials were found between relatively slow and fast speeds or absolute values of the speeds during habituation.

In conclusion, the results of the present experiments show that infants' speed discrimination is modulated by Weber's law and increases in precision between 6 and 10 months of age. The parallels in acuity between duration, size, number, and speed discrimination suggest a common underlying mechanism that infants employ to represent information in all four domains. Future research should expand on this hypothesis by directly testing infants' abilities in those domains using comparable methods and stimuli.

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Footnotes

[1] Non-habituators were included in this and subsequent experiments because results did not differ when they were excluded.

[2] To test whether the particular speed of 5 cm/s which served in one group as “slow” and in the other group as “fast” resulted in differences in infants’ looking behavior, we performed an additional analysis in which we compared infants who were habituated to the slower speed in the “slow” condition and the faster speed in the “fast” condition (i.e., to 2.5 cm/s and 10 cm/s) and found that both groups did not differ in their looking times toward the novel speed (i.e., 5 cm/s in both cases), $t(10) = .83$, $p < .05$.

Table 1.

Values of the time, distance, and speed dimensions in habituation and test trials of Experiment 1.

Speed	2.5 cm/s		5 cm/s		10 cm/s	
	Time (s)	Distance (cm)	Time (s)	Distance (cm)	Time (s)	Distance (cm)
Habituation						
H1	2.5	6.25	1.5	7.5	1.5	15
H2	1.5	3.75	2	10	1	10
H3	3	7.5	1	5	0.5	5
H4	2	5	2.5	12.5	2	20
Test Trial						
T1	2.25	5.625	1.75	8.75	1.25	12.5

Table 2.

Mean looking times to the familiar and novel test trials for 6- and 10-month-old infants separately for each habituation condition and absolute value group.

Experiment 1 (6-month-old infants, ratio 1:2)

		Test	
		Familiar	Novel
Habituation condition	slow speed	12.72 (2.65)	16.63 (2.81)
	fast speed	9.01 (1.09)	14.41 (1.68)
Absolute value	5 and 10 cm/s	12.30 (2.41)	18.06 (2.32)
	2.5 and 5 cm/s	9.44 (1.62)	12.98 (2.10)

Experiment 2 (6-month-old infants, ratio 2:3)

		Test	
		Familiar	Novel
Habituation condition	slow speed	10.03 (1.40)	9.77 (1.72)
	fast speed	8.77 (2.34)	11.01 (2.09)
Absolute value	5 and 7.5 cm/s	8.67 (2.37)	9.86 (1.79)
	6.66 and 10 cm/s	10.13 (1.32)	10.93 (2.03)

Experiment 3 (10-month-old infants, ratio 2:3)

		Test	
		Familiar	Novel
Habituation condition	slow speed	6.70 (0.70)	9.53 (1.65)
	fast speed	6.52 (0.90)	10.52 (1.40)
Absolute value	5 and 7.5 cm/s	6.22 (0.75)	10.21 (1.66)
	6.66 and 10 cm/s	7.00 (0.84)	9.85 (1.41)

Note. Standard Errors are presented in parentheses.

Table 3.

Values of the time, distance and speed dimensions in habituation and test trials of Experiment 2 and 3.

Speed	6.66 cm/s		7.5 cm/s	
	Time (s)	Distance (cm)	Time (s)	Distance (cm)
Habituation				
H1	1.5	10	1.5	11.25
H2	2	13.32	1	7.5
H3	1	6.66	0.5	3.75
H4	2.5	16.65	2	15
Test Trial				
T1	1.75	11.655	1.25	9.375

Figure Captions

Figure 1. Mean looking time to the first three and last three habituation trials and the familiar and novel test trials for infants at the age of 6 months examined with speeds differing in a 1:2 ratio. Error bars indicate standard errors.

Figure 2. Mean looking time to the first three and last three habituation trials and the familiar and novel test trials for infants at the age of 6 months examined with speeds differing in a 2:3 ratio. Error bars indicate standard errors.

Figure 3. Mean looking time to the first three and last three habituation trials and the familiar and novel test trials for infants at the age of 10 months examined with speeds differing in a 2:3 ratio. Error bars indicate standard errors.

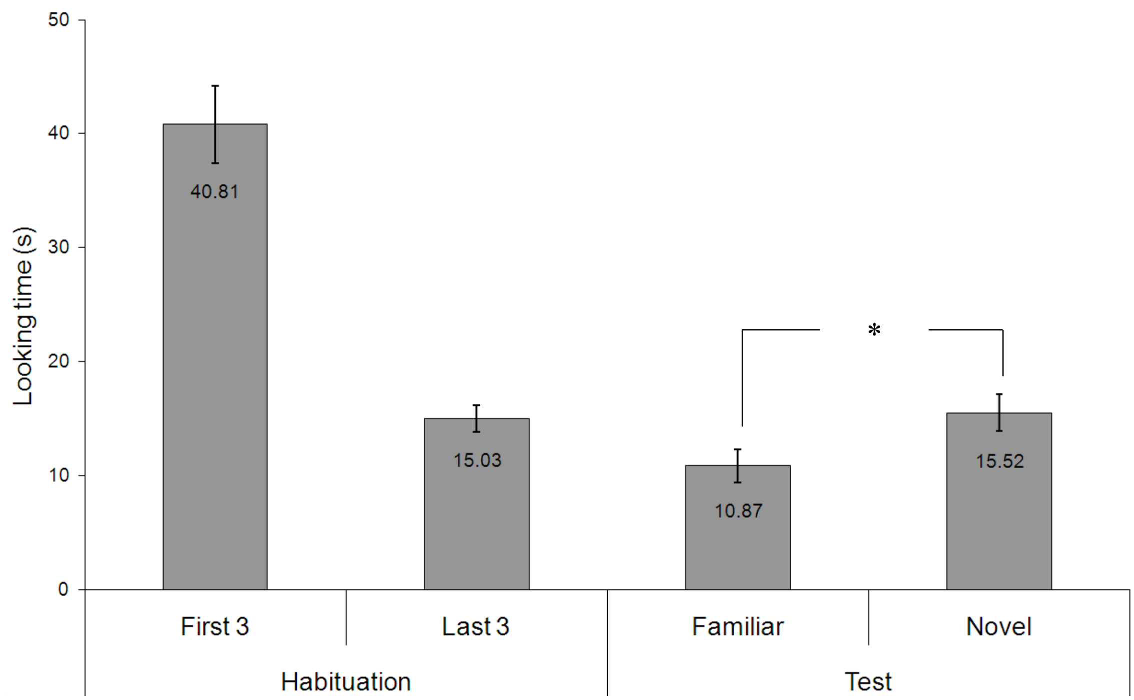
50
40
30
20
10
0
Looking time (s)
40.81
15.03
10.87
15.52
*
First 3
Last 3
Familiar
Novel
Habituation
Test

Figure 1.

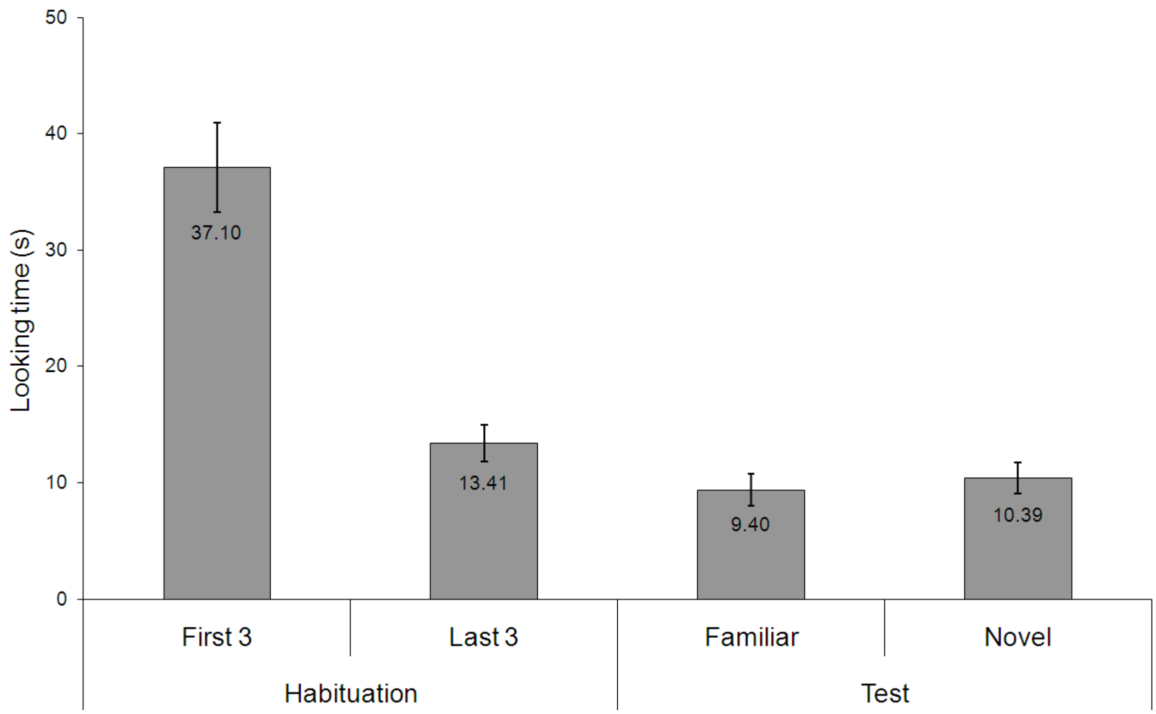
50
40
30
20
10
0
Looking time (s)
37.10
13.41
9.40
10.39
First 3
Last 3
Familiar
Novel
Habituation
Test

Figure 2.

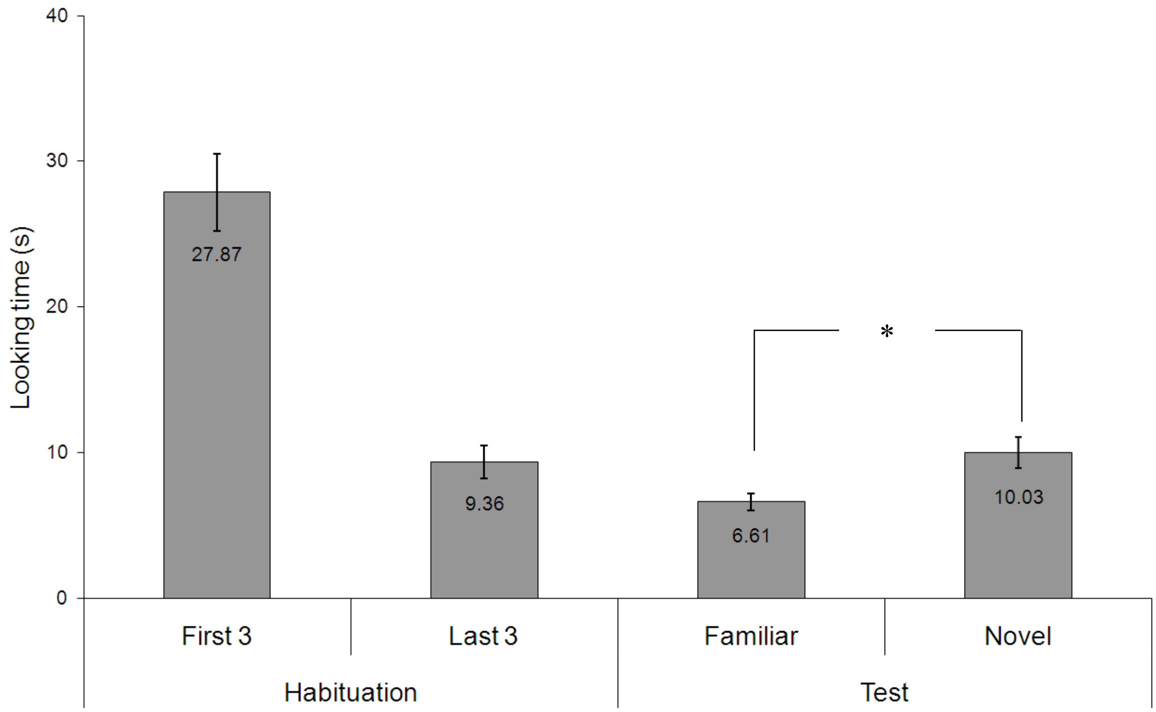
40
30
20
10
0
Looking time (s)
27.87
9.36
6.61
10.03
*
First 3
Last 3
Familiar
Novel
Habituation
Test

Figure 3.

On the origin of the understanding of time, speed, and distance interrelations

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3. On the origin of the understanding of time, speed, and distance interrelations

3.1 Abstract

We examined 18- and 24-month-old infants’ sensitivity to the functional relationships between time, speed, and distance. The task included a train moving first visibly and then into a tunnel. The movement of the train was always accompanied by a train-characteristic sound signalling the travel duration. After the train concluded its travel, infants were requested to search for it in two possible locations inside the tunnel. Infants’ reaching and head turn behavior indicated that 24-month-olds were sensitive to time-speed-distance interrelations, while 18-month-olds showed no such understanding. Reducing occlusion duration (by shortening the tunnel’s length) revealed an increase in 18-month-olds’ reaching and anticipatory head turns. Results are discussed in terms of the developmental course of the understanding of time-speed-distance interrelations and the strength of infants’ representations.

Wordcount: 124

Keywords: Time-Speed-Distance Interrelations; Physical Reasoning; Cognitive Development; Object Representations; Infants

3.2 Introduction

Infants are constantly confronted with objects that move in and out of sight. The understanding of such dynamic events is especially important to predict the future behavior of objects and to plan and control one's own actions accordingly. There is now ample evidence illustrating infants' astonishing perceptual sensitivity toward various spatiotemporal aspects of object motion (Gredebäck & von Hofsten, 2004; Johnson et al., 2003; Leslie, 1984; Rosander & von Hofsten, 2004; Spelke, Kestenbaum, Simons, & Wein, 1995; van der Meer, van der Weel, & Lee, 1994; von Hofsten, 1980; von Hofsten, Feng, & Spelke, 2000; von Hofsten, Kochukhova, & Rosander, 2007; von Hofsten, Visthon, Spelke, Feng, & Rosander, 1998; Wilcox & Schweinle, 2003). Infants were found to be sensitive to spatiotemporal continuity, inertia, and the dynamics of an object's movement.

Infants (and adults) expect objects to move on continuous paths in time and space. That is, they expect an object to traverse the spatial path between different locations within an appropriate time frame. If this basic physical law is violated, infants (and adults) draw conclusions accordingly. For example, Spelke and colleagues presented 5-month-old infants with a rod that moved sequentially behind two screens, which were positioned at spatially separated locations. Infants' looking behavior indicated that they regard this rod as one discrete moving object when it traversed the path between the screens. When the rod did not appear between the two screens, infants' looking behavior suggested that they perceived two individual objects (Spelke et al., 1995). Spatiotemporal continuity is a key principle that guides object persistence and refers to a phenomenon of visual cognition, namely *spatiotemporal priority* (Scholl, 2001, 2007). This phenomenon points to the vital role of spatiotemporal information and means that infants (as adults) often judge spatiotemporal information as more important for object perception and individuation than featural information (cf. Xu & Carey, 1996).

Studies of infants' predictive abilities showed that infants' anticipations take the principle of inertia (objects preserve their present state of rest or consistent motion unless acted upon by forces) into account. In a study by von Hofsten and colleagues (2000) 6-month-old infants were presented with objects that moved along diagonal trajectories that intersected at the occluded center of the display. Once set in motion along one diagonal, the object either continued to move along the same diagonal or changed its direction at the intersection. While infants' predictive head turns indicated that they expected the object to continue its linear movement, they also learned, albeit slowly, to expect nonlinear changes. Consequently, results imply that infants expect forces that affected the object's motion prior to occlusion to continue during unseen parts.

Another important finding is that infants preserve the spatiotemporal properties of the occluded motion and manage to "track [the object] with their mind's eye" (Gredebäck & von Hofsten, 2004, p. 182). More specific, Gredebäck and von Hofsten (2004) demonstrated that 6- to 12-month-old infants were able to predict where and when temporarily occluded objects reappear. Infants were presented with objects that traveled with different speeds on circular trajectories and were temporarily occluded (occlusion ranging from 0.5 to 4 s). Results suggest that infants are able to represent parameters of the object's movement during temporal occlusion. Moreover, it was found that latency of gaze shifts was a function of occlusion duration. That is, at all ages did infants' predictions take occlusion duration into account.

The above mentioned studies show that infants confronted with temporarily occluded objects expect continuous, inert movements, and that they preserve and use motion parameters to make correct anticipations. However, it remains an open question whether infants are sensitive toward the interrelations of the motion parameters (i.e., time, speed, distance). For example, in order to correctly infer when a temporarily occluded object will reappear, infants must have some notion about the relationship between time and distance (i.e., it will take longer to traverse a long tunnel than a short one at equal speed). Results of Gredebäck and von Hofsten (2004) suggest that infants have such an early awareness (given that latency of gaze shifts was adjusted to occlusion duration). However, to our knowledge it was never systematically investigated whether infants consider time, speed, and distance interrelations (TSD) when predicting the whereabouts of moving objects. That is, are infants able to infer values of one dimension (e.g., distance) when given the values of the other two dimensions (e.g., time and speed)? In other words, do infants have a functional understanding of TSD interrelations in the sense that they apply rule-based reasoning? The purpose of the present study was to investigate this question and provide insights in infants' sensitivity to the functional relationships between TSD.

The understanding of TSD interrelations was investigated by researchers within the field of children's intuitive physics (Acredolo, Adams, & Schmid, 1984; Acredolo & Schmid, 1981; Matsuda, 1994, 2001; Piaget, 1946a, 1946b, 1975; Siegler & Richards, 1979; Wilkening, 1981, 1982). According to Piaget (1946a, 1946b, 1975), children's knowledge of the relationships between TSD undergoes a lengthy development. In a typical Piagetian task, two toy trains traveled on parallel tracks for either different durations, or with different speeds, or over different distances. Children were requested to choose the train which goes for a longer time, with higher speed, or traveled more distance. While initially children's judgments about time and speed were often confounded by representations of distance, children mastered these concepts quite late in their development around the age of 9 to 10 years.

Evidence that children from the age of 5 years have an intuitive knowledge about TSD interrelations was provided by studies using the method of functional measurement (Wilkening, 1981, 1982). The rationale behind functional measurement is to provide children with values of two dimensions of the TSD-triad and let them infer the value of the third dimension (Anderson, 1981, 1982; Anderson & Wilkening, 1990). In one application of this method, children had to infer how far an animal would escape from a barking dog (distance) while information about the quickness of an animal (speed) and the duration of a dog's barking (time) was varied. Wilkening found that 5-year-olds correctly integrated the given dimensions to infer values of distance, but correct inferences about time and speed awaited further development. The author concluded that children have an implicit knowledge about TSD interrelations, but that the distance concept (involving a multiplying integration rule) develops before the speed and time concept (each of them involving a dividing integration rule). On the basis of this conclusion the author reasoned that understanding of direct relationships of the TSD constituents precede understanding of the inverse relationship. That is, they master the direct relationship between a) time and distance (e.g., *more* time is related to *more* distance) and b) speed and distance (e.g., *more* speed is related to *more* distance) before the inverse relationship between c) speed and time (e.g., *more* speed is related to *less* time). This conclusion was later confirmed. While 4-year-old children demonstrated an understanding of the direct relationships between TSD, they did not show an understanding of the inverse relationship until the age of 7 years (Albert, Kickmeier-Rust, & Matsuda, 2008; Matsuda, 1994, 2001).

While these studies show children's correct inferences of travel distance when given information about the travel time and speed, there are virtually no studies investigating younger age groups. Although the above mentioned infant studies point to an early sensitivity to spatiotemporal information of an object's motion, infants' rule-based understanding between different dimensions and their ability to infer one from the other was to our knowledge never investigated. Therefore, the present study was intended to be a first step in closing this gap between studies of children's intuitive physics and studies about infants' early sensitivity toward various aspects of object movement. With the following experiments, we aimed to provide answers to the question of whether infants are sensitive to the functional relationship between TSD, and whether they infer values of one parameter when values of the other two parameters were presented.

Given previous findings suggesting that children's understanding of direct relationships precede the understanding of the inverse relationship between TSD (Matsuda, 1994, 2001; Wilkening, 1981, 1982), we started our investigation by examining infants' sensitivity to the direct relationship between time and distance (at constant speed). Identical to research designs used with older children (Matsuda, 1994, 2001; Wilkening, 1981, 1982), infants were presented with information about two dimensions (speed and time) and their ability to infer the value of the third dimension (distance) was measured. We employed an action-based task which was adapted from studies investigating children's intuitive physical understanding (Matsuda, 2001; Wilkening, 1981). In particular, a toy train moved with constant speed first visually and then into a tunnel with two openings—one that was close to the start location of the train (near tunnel) and one that was located at the end of the track (far tunnel). Movement of the train was accompanied by a sound, which was presented every time and only if the train moved. After the train reached its final location, signaled by the end of the sound, infants were asked to search for it in the two hiding locations. If infants are sensitive to the functional relationship between time and distance they are expected to search (1) in the near tunnel after hearing a sound indicating a short travel time and (2) in the far tunnel after hearing a sound indicating a long travel time. While studies using analogous action-based tasks examined infants in an age range of 2 to 3 years (Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Hood, Carey, & Prasada, 2000), we decided to examine infants in an age range of 1.5 to 2 years and assessed both infants' reaching and head turn behavior. On the one hand, a multi-measurement approach offers a more detailed monitoring of the developmental progress in infants' representations of TSD interrelations. On the other hand, it allows examining possible dissociations in infants' reaching and looking behavior (see e.g., Hood, Cole-Davies, & Dias, 2003; Jonsson & von Hofsten, 2003).

3.3 Experiment 1

3.3.1 Method

Participants. Twenty healthy and full-term 24-month-old infants (mean age = 24 months and 9 days, *SD* = 5 days, 10 males) and 20 18-month-old infants (mean age = 18 months and 2 days, *SD* = 9 days, 10 males) participated in the present experiment. One additional 18-month-old infant participated in the study but was excluded from the final sample due to fussiness. Participants in this and the following experiments were recruited by telephone from a pool of families who had volunteered to take part in studies of child development. Parents filled out a consent form before taking part in our study and infants received a small gift for their participation.

Apparatus. The apparatus consisted of a horizontal wooden track, a toy train that moved from the left side of the track to the right, and a set of tunnels (see Figure 1). The wooden track was 1.5 cm high, 160 cm long and 6 cm wide. The track was attached to the surface of a table with the left side exceeding the table's edge by 12 cm. The tunnels (two blue ones and one white tunnel) were made out of hard cardboard. Each blue tunnel was 15 cm high, 12 cm long and 12 cm wide. They had an opening (13 high × 8 cm long) in the front side that was covered by a red curtain. The blue tunnels were connected by a large white tunnel (15 cm high × 56 cm long × 12 cm wide). The tunnels were placed at the right end of the track. Thus, the movement of the train was visible for the first 70 cm and concealed for the last 80 cm. The first 10 cm of the track were occupied by the stationary train.

The toy train was 6.5 cm high, 10 cm long and 5 cm wide. It produced a train-characteristic sound when moving. Because it was a clockwork train, it moved by itself when it was wound up. At the beginning of each trial the train was wound up three times and placed at its starting position at the left end of the track. The wound up train was held in place by a wooden lever. Upon releasing the position lever, the train started to move with a constant speed of 25 cm/s. It moved for 3.2 s before it entered the near tunnel (short distance) and for 5.84 s before it entered the far tunnel (long distance). Thus, with given speed and travel time, the train covered a distance of 80 cm and 146 cm, respectively. To prevent that infants locate the positions of the train by simply orienting toward the sound emitted by the train, we overshadowed it by presenting an additional train-characteristic sound through two loudspeakers placed to the left and right of the track.

The train moved from the child's left to its right and could be stopped by a small rigid barrier within the near or far tunnel. Foam was glued onto the barrier's surface to absorb any impact sound. Before starting the movement of the train, the experimenter inconspicuously positioned the barrier in the near or far tunnel. When placing the barrier on the track the experimenter always reached with both hands into both tunnels, in order to give no clue as to where the train will stop.

Design and Procedure. The experimental session started with the infant sitting on their caregiver's lap facing the apparatus. Parents were asked to look at the back of their infant's head during the experiment to prevent interference. Infants were seated between the near and far tunnel, so that reaching distance to each tunnel was identical. The experimenter sat across from the infant facing the back of the apparatus.

First, a familiarization was conducted in which the toy train moved twice the full length of the track without being hidden by any tunnel. In this and the following movements, the train's sound was always overshadowed by presenting an additional train-characteristic sound. Thereafter, the near and far tunnel were placed at their locations on the track and the train moved again twice from left to right but was stopped between the tunnels. The reason of this familiarization was to provide infants with information about speed and sound of the train and to show its ability to move through the tunnels. Furthermore, familiarization aimed to present infants with information about the connection between the train's movement and the movement-linked sound. Given that young infants have been frequently shown to connect sound and movement (Walker, 1982, Walker-Andrews & Lennon, 1985), infants of the present experiments were expected to associate movement and sound. Importantly, Srinivasan and Carey (2010) illustrated recently that 9-month-old infants were able to bind particular spatial lengths with the appropriate temporal durations, indicating a functional overlap between spatial and temporal representations.

After familiarization, the large white tunnel was presented and positioned between the two blue ones. The train was hidden in one of the blue tunnels and shown to the infant. Infants were encouraged to reach and retrieve the train. This procedure was repeated until the infant reached at least once into each tunnel. Half of the infants were first exposed to the near and then to the far tunnel and half of the infants were exposed to the reversed order. All infants successfully searched for the train in both tunnels.

Immediately after familiarization and warm-up reaching, the test trial was presented, in which the train moved either to the near tunnel (short distance) or to the far tunnel (long distance). Half of the infants were presented with a short distance test trial and the other half with a long distance test trial. At the beginning of the test trial, the experimenter pointed to the train, which rested at the beginning of the track in order to direct infant's attention toward the train. Immediately after the infant looked at the train, the position lever was removed to set the train into motion. During the train's movement the experimenter looked down at the table to avoid inadvertently cueing the infant. After the train stopped at its final location in the tunnel (either near or far tunnel), the experimenter looked at the infant and asked "Where is the train?" and requested the infant to search. As soon as the infant retrieved the train, the trial was finished. If the infant did not react within the first 10 s, the question was repeated and the experimenter tapped three times on both tunnels simultaneously.

Moreover, infants were classified as performing an anticipatory head turn when the infant turned his/her head toward the correct tunnel (i.e., the near or far tunnel) while the train was hidden in the tunnels. Infants' reaching and head turn behavior was coded off-line from video tape. Ten randomly chosen participants within each age group were coded by another naïve experimenter to calculate interobserver reliability. Cohen's kappa was 1.0 for reaching, and 1.0 for head turn behavior.

3.3.2 Results and Discussion

The reaching and head turn behavior of the 24- and 18-month-old infants is depicted in Figure 2. While 24-months-olds reached significantly more often to the correct location of the train (75%, Binomial, $p < .05$), the 18-month-olds' reaching behavior was at random (50%, Binomial, $p = 1.0$). However, directly comparing the reaching behavior of the two age groups revealed no significant differences ($p = .095$, one-tailed Fisher's exact test). In both age groups, gender, order of the warm-up, and, most notably, the particular test event (short vs. long distance test) did not influence infants' reaching behavior ($p > .05$ in all cases). In addition, 80% of the 24-month-olds performed an anticipatory head turn to the correct location (Binomial, $p < .05$) while only 55% of the 18-month-olds showed this behavior (Binomial, $p = .82$). Again, comparing the anticipatory head turn behavior in the two age groups revealed no reliable difference ($p = .088$, one-tailed Fisher's exact test).

Our findings show that at least 24-month-old infants were sensitive to the direct relation between the duration of the object's movement (indicated by the sound) and the travel distance, as evidenced in their correct reaching behavior and anticipatory head turns. That presumes that infants expected a continuous and inert movement during occlusion and were aware of the constant speed of the train. Beyond that, they were able to infer the correct displacement location after being presented with different values of the time dimension. In contrast to that, 18-months-olds' reaching and head turn behavior was randomly. Although their performance did not reliably differ from that of the 24-month-olds, they failed to anticipate and reach to the correct final location of the train, indicating that they were not sensitive to the direct relation between time and distance.

What might be the source of the observed age differences? First of all, it is conceivable that the occlusion duration was taxing for the younger age group's representational system. In fact, recent research suggests a negative effect of occlusion duration on infants' anticipatory reaching behavior. For example, in a task in which infants had to reach for temporarily occluded objects moving with varying speeds, van Wermeskerken, van der Kamp, te Velde, Valero-Garcia, Hoozemans, and Savelsbergh (2011) found that increasing occlusion duration led to a decrease in infants' correct reaching performance. Various cognitive accounts attempt to explain why occlusion duration may affect infants' performance. The graded-representations account posits that infants' representations are not all-or-none entities but graded in nature (Munakata, McClelland, Johnson, & Siegler, 1997; Shinskey & Munakata, 2005, Spelke & von Hofsten, 2001). That is, knowledge representations are not just present or absent, but graded in strength and become gradually more precise over development. In light of this view, a decrease in occlusion duration might increase 18-month-old infants' performance, considering this age group's representations are not yet strong enough to deal with longer occlusion durations.

Similarly, the cognitive-load account proposes that infants' limited processing capacities are negatively influenced by increases in the overall cognitive load of a task (e.g., by additional motor demands) (Berthier et al., 2001, Boudreau & Bushnell, 2000; Keen, Carrico, Sylvia, & Berthier, 2003). Thus again, infants should profit from a decrease in occlusion duration because it decreases the cognitive load of the task.

Taking these considerations into account, we decided to reduce occlusion duration by shortening the tunnel's length within the next experiment. We expected this manipulation to lead to more correct search and head turn behavior in 18-month-old infants.

3.3 Experiment 2

3.4.1 Method

Participants. Twenty healthy and full-term infants at the age of 18 months participated in this experiment (mean age = 18 months and 6 days, *SD* = 9 days; 10 males).

Apparatus. The apparatus was identical to the one in Experiment 1 except for the following change. The white tunnel between the two blue ones was reduced in length from 56 cm (Experiment 1) to 30 cm. The size of the blue tunnels was the same as in Experiment 1. Thus, the tunnels (two blue and one white tunnel) covered now 54 cm of the track. To keep the visible part of the train's movement identical to Experiment 1, the tunnels were placed again 70 cm from the train's starting point, resulting in a total track length of 134 cm. Thus, while travel time and distance to reach the near tunnel were identical to Experiment 1, these movement parameters changed to 4.8 s and 120 cm to reach the far tunnel in Experiment 2.

Procedure. Procedure and coding were analogously to Experiment 1. Ten randomly chosen participants were coded by another naïve experimenter to calculate interobserver reliability. Cohen's kappa was 1.0 for reaching, and 1.0 for head turn behavior.

3.4.2 Results and Discussion

Eighteen-month-old infants reached significantly correct to the final location of the train (85%, Binomial, $p < .01$). Moreover, infants' reaches in the present experiment were significantly more often correct than reaches of the 18-month-olds in Experiment 1 ($p < .05$, two-tailed Fisher's exact test). Gender, order of the warm-up reaching and the particular test event (short vs. long distance test) did not significantly influence infants' reaching behavior ($p > .05$ in all cases). In addition, 95% of the 18-month-olds performed an anticipatory head turn to the correct location (Binomial, $p < .001$), which constitutes a significant difference to the head-turn behavior of the 18-month-olds in Experiment 1 ($p < .01$, two-tailed Fisher's exact test).

Reducing the occlusion duration led to a reliable increase in both 18-month-olds' anticipatory head turns and their reaching behavior. As the 24-month-olds in Experiment 1, the 18-month-olds in Experiment 2 correctly anticipated and reached toward the final location of the train. Thus, if the task is tailored to meet younger infants' cognitive capacities (i.e., shorter occlusion durations), a sensitivity to the direct relationship between time and distance is already observed by an age of 18 months. Like older infants, they are then able to infer values of one dimension (distance) after being presented with values of the others (time and speed). The positive influence of reducing occlusion duration is consistent with recent findings (van Wermeskerken et al., 2011) and provides supportive evidence for the graded-representations and the cognitive load account (Berthier et al., 2001; Keen et al, 2003; Munakata, 2001; Spelke & von Hofsten, 2001).

3.4 General Discussion

The aim of the present study was to provide initial insights into the origin and developmental course of a sensitivity toward TSD interrelations. We were able to demonstrate that at the age of 24 months, infants made correct inferences about the travel distance of a moving object. That is, they were able to infer values of one dimension (distance) from the others (speed and time) and thus, seem to have a rule-based sensitivity about the direct relation of time and distance. Given infants' correct inferences in the present experiments, we can presume that they perceived the movement as continuous and inert and were aware of the constant speed of the object. Most importantly, infants inferred (1) a short travel distance when hearing a sound indicating a short travel time and (2) a long travel distance when hearing a sound indicating a long travel time. In contrast, 18-month-olds demonstrated this understanding neither in their reaching behavior nor in their anticipatory head turns when tested with the same long tunnel as the 24-month-olds (Experiment 1). Under conditions when occlusion duration was reduced (Experiment 2), 18-month-olds' anticipatory head turns and their reaching behavior increased in correctness, indicating that even at this age, infants are sensitive to the direct relation between time and distance.

Research investigating children's intuitive physics (Matsuda, 1994, 2001; Wilkening, 1981, 1982) demonstrated that children at the earliest of 4 years had an intuitive knowledge about the direct relations between TSD. We can extend this finding by suggesting that earliest signs of this understanding are found at the age of 18 months. Our non-verbal action-based task was an adaptation of the one used by Matsuda (2001) and Wilkening (1981) with older verbal children. It has been repeatedly shown that with a sensitive task, even young infants evidence abilities that are thought to be accomplishments of older children.

Our findings are in accordance with several results from previous studies. First, infants in our study were able to predict the travel distance of a moving object, which agrees with infants' predictive behavior in other studies (Jonsson & von Hofsten, 2003; Rosander & von Hofsten, 2004; van der Meer et al., 1994; von Hofsten et al., 2007). Second, infants in our experiments were also sensitive to several physical laws like continuity and inertia that govern objects in motion (Johnson et al., 2003; Spelke et al., 1995; von Hofsten et al., 2000; von Hofsten et al., 1998). Third, our results point to a strong effect of occlusion duration on infants' cognitive processes and their subsequent behavior. This is evident in 18-month-olds' enhanced performances during shorter (Experiment 2) compared to longer occlusion durations (Experiment 1). Given that the experimental set-ups and designs of both experiments were completely identical except of the different occlusion periods, it is highly unlikely that infants' enhanced performance during Experiment 2 was due to other factors than occlusion duration. During shorter occlusion durations (Experiment 2), infants reached and anticipated more correctly than expected by chance which was not the case for same-aged infants tested with longer occlusion durations. This finding of enhanced performance is in accordance with recent empirical evidence (van Wermeskerken et al., 2011) and supports assumptions of the graded-representations and the cognitive load account (Berthier et al., 2001; Keen et al, 2003; Munakata et al., 1997; Shinskey & Munakata, 2005). That is, infants' representations of the moving object became less precise with increased occlusion duration (according to the graded-representations account) or the overall cognitive load of the task increased with longer occlusion durations (according to the cognitive load account). However, while the occlusion duration of Experiment 2 supported 18-month-olds' correct reaches and anticipations, the occlusion duration of Experiment 1 (which was 1.04 s longer) seemed to exceed their representational capacity, resulting in degraded behavior (e.g., less reaches and anticipatory head turns).

Twenty-four-month-olds' correct inferences during longer occlusion durations (Experiment 1) show that infants' ability to tolerate occlusion durations enhances with increased age. One possible explanation is that the precision of object representations improves with increased age (e.g., see Munakata et al., 1997; Spelke & von Hofsten, 2001). As infants get older, the rate of accuracy loss in representations decreases. In turn, this decline results in higher tolerances for long occlusion durations and thus, longer sustainment of the representations.

Regarding our findings, we can conclude that infants' sensitivity to the direct relationship between time and distance in the present task was dependent on factors (like occlusion duration) that in general influence cognitive processes. Consequently, we agree with Munakata and colleagues (1997) in that reaching and looking performances "[are] a function of the state of development of both task-specific mechanisms and representational systems" (p. 690).

Ultimately, our findings provide further insights into the development of physical reasoning, and in particular add to our understanding of the early development of the functional relationships between TSD. In addition, the use of the present action-based task was found to be a valuable method in closing the gap between looking-time studies carried out with young infants and verbal tasks conducted with older children. Our data imply that 18-month-old infants are aware of the "more is more" relation between time and distance dimensions and correctly infer values of the distance dimensions from values of the time and speed dimensions. Importantly, these correct inferences are dependent on the representational strength of the infant's cognitive system. However, up to now many questions remain unanswered. For example, whether infants younger than 18 months show a sensitivity to the direct relations between TSD and whether infants' sensitivities toward both direct relations within TSD interrelations (between time and distance as well as speed and distance) are similar in their developmental trajectory. Currently, we are investigating these questions.

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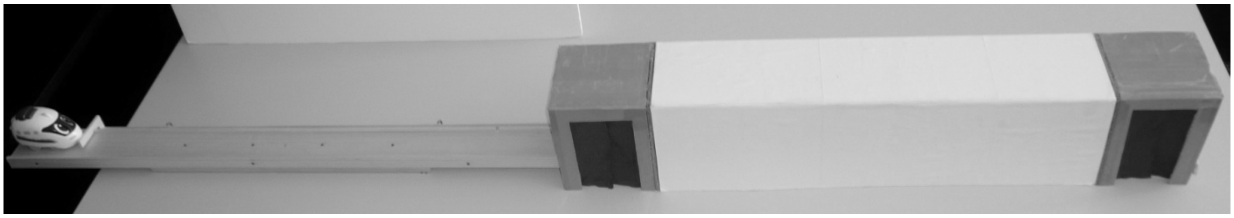
Figure Captions

Figure 1. View of the apparatus with the toy train resting at the left side of the track.

Figure 2. Percent correct responses for 24-month-old and 18-month-old infants tested in Experiment 1 and 2.



Start Position Near Tunnel Far Tunnel

Figure 1.

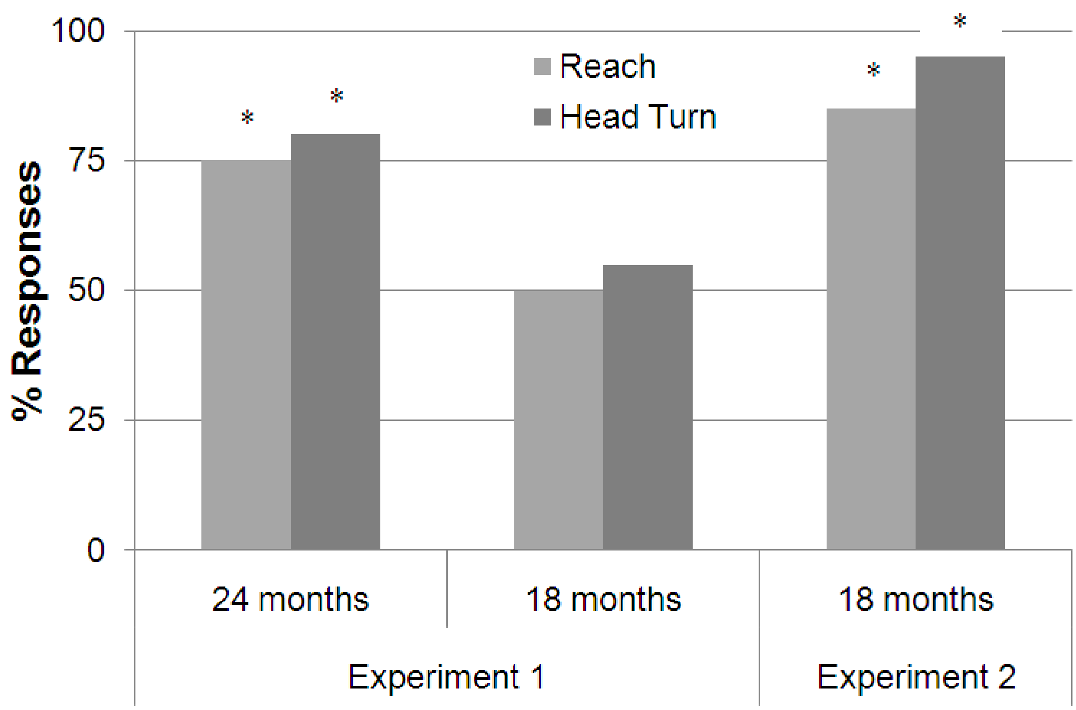

100
75
50
25
0
% Responses
Reach
Head Turn
*
*
*
*
24 months
18 months
18 months
Experiment 1
Experiment 2

Figure 2.

Infants' anticipatory eye movements reveal infants' sensitivity to the travel distance

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4. Infants' anticipatory eye movements reveal infants' sensitivity to the travel distance

4.1 Abstract

Using an eye tracking device, we investigated 12- and 18-month-olds' sensitivity to the interrelations that exist between time, speed, and distance dimensions (TSD). Infants were presented with computer-animated scenes in which an object moved several times behind an occluder. Movement of the object was always accompanied by a sound that indicated how far the object had moved. Before the occluder was lowered to reveal the object's final position, infants' visual anticipations regarding the object's travel distance were measured. Results indicated that 18-month-olds were sensitive to TSD interrelations while infants at the age of 12 months lingered at the object's disappearance location, indicating that 12-month-olds' behavior was driven by a proximity bias. Findings are discussed in terms of the developmental course of the understanding about TSD interrelations.

Wordcount: 126

Keywords: Time-Speed-Distance Interrelations; Physical Reasoning; Infants

4.2 Introduction

From an early age on, infants are able to track objects that move around in their environment. While tracking of a visibly moving object is a relatively easy task, the tracking and anticipation of a temporarily occluded object poses a special challenge. Not only need infants to understand that objects move on continuous and inert paths, but they also need to represent spatiotemporal information in order to make correct inferences about when and where the object will reappear. Importantly, such predictions also require an understanding of time, speed and distance interrelations (TSD) given that these dimensions and their interplay determine every movement. For example, one needs to appreciate that particular values of one dimension (e.g., a longer travel time) are related to values of another dimension (e.g., a longer travel distance) when the third one (e.g., speed) is held constant.

Literature has repeatedly shown that infants are sensitive to several physical laws that govern objects in motion. For example, already very young infants expect objects to move and exist continuously in time and space (Johnson et al., 2003; Spelke, Kestenbaum, Simons, & Wein, 1995; Wilcox & Schweinle, 2003). That is, 5-month-old infants interpret an event as existing of one object if the object traversed the path between two screens while they perceive the same event as existing of two objects when the object did not appear between these screens (Spelke et al., 1995). Furthermore, researchers illustrated that 6-month-old infants perceive inert, and thus linear object movements (von Hofsten, Feng, & Spelke, 2000; von Hofsten, Visthon, Spelke, Feng, & Rosander, 1998). In these studies, 6-month-old infants expected objects to preserve their present state of consistent motion unless acted upon by forces. Studies using eye-tracker methodologies also indicate that 6- to 12-month-old infants represent the spatiotemporal dynamics of an object motion and are able to predict where and when a temporarily occluded object will reappear (Gredebäck & von Hofsten, 2004). Latencies of gaze shifts performed by all age groups were thereby a function of occlusion duration, showing that infants took occlusion duration into account when executing an anticipatory gaze shift.

These studies indicate that infants expect continuous, inert movements and are able to represent the spatiotemporal dynamics of an object's motion. However, for making correct anticipations infants need to be sensitive to the interrelationships of TSD dimensions. Reasoning on the basis of TSD interrelations is important when, for example, determining which of two objects with equal travel time will cover more distance, the slow- or fast-moving one, or deciding in which case an object with constant speed requires longer to reappear, the one travelling behind a narrow or wide occluder. Results of Gredebäck and von Hofsten (2004) indicate that infants have an early awareness of TSD interrelations (because latencies of gaze shifts depended on occlusion duration). However, it has not been systematically explored whether infants are able to infer values of one dimension (e.g., distance) when information about the other two dimensions (e.g., time and speed) are given. That is, the investigation of infants' rule-based understanding of TSD interrelations has been sparse.

In a first attempt, infants' sensitivity to TSD interrelations was investigated in a recent study by Möhring, Cacchione, and Bertin (2012). Employing an action-based task, 18- and 24-month-old infants were presented with a train that moved with constant speed on a horizontal track, first visually and then into a tunnel. The movement of the train was always accompanied by a continuous sound that indicated how far the train had moved within the tunnel. After the sound stopped (indicating the end of the train's movement), infants were requested to search for the train in two possible hiding locations—either at the beginning or the end of the tunnel. Correct search behavior of the 18-month-old infants was found to be task-dependent. That is, they only demonstrated correct anticipations in their reaching and head turn behavior when the tunnel's length was short, thus reducing occlusion duration of the train's movement. Twenty-four-month-old infants were able to reach and turn their head to the correct hiding location regardless of the object's occlusion duration, illustrating that the representational strength of the older infants' cognitive system is able to tolerate longer concealment durations. This study illustrated that under optimal testing conditions even 18-month-olds have a rule-based understanding of the direct relationship between time and distance. That is, 18-month-old infants were able to correctly infer values of the distance dimension after being presented with values of the time and speed dimensions. These findings extend what is known about children's understanding of TSD interrelations.

Children's understanding of TSD interrelations has been investigated within the area of children's intuitive physics (Acredolo & Schmid, 1981; Matsuda, 1994, 2001; Piaget, 1946a, 1946b, 1975; Siegler & Richards, 1979; Wilkening, 1981, 1982). While Piaget (1946a, 1946b, 1975) claimed that children master these concepts after a lengthy developmental construction at the age of 9 to 10 years, other researchers showed that even younger children are sensitive toward TSD interrelations (Matsuda, 1994, 2001; Wilkening, 1981, 1982). For example, in a task used by Wilkening (1981, 1982), 5- and 10-year-old children as well as adults were presented with an animal that fled from a barking dog. Participants were requested to estimate how far the animal could flee (distance) while information about the quickness of the animal (speed) and the duration of the dog's barking (time) was varied. Analogous tasks were created to test children's and adults' inferences about time and speed. Findings showed that even at the age of 5 years, children correctly integrated the given dimensions to estimate distance (using a multiplying integration rule), but correct estimations for time and speed (both of them requiring a dividing integration rule) awaited further development. While inferences for the time dimension were correct at the age of 10 years, estimations for the speed dimension proved to be difficult even for adults. Based on these findings, Wilkening concluded that the development of the distance concept precedes the development of the speed and time concept. Furthermore, it seems that direct relationships (i.e., between time and distance as well as distance and speed) are mastered at an earlier age than the inverse one (i.e., between time and speed).

As mentioned above, the recent study by Möhring and colleagues (2012) suggested that even 1.5-year-olds correctly inferred values of the distance dimension. By doing so, infants demonstrated that even at this early age, they are sensitive to the direct relationship that exists between the time and distance dimension. Building upon these findings, we aimed to further investigate infants' ability to infer travel distance. The aim of the present study was two-fold. First, we wanted to replicate previous findings by re-examine 18-month-olds' visual anticipations using an eye tracking device. Second, we were interested in the developmental trajectory of infants' sensitivity to TSD interrelations, and thus examined whether infants younger than 18 months are able show correct inferences about an object's travel distance.

In the present study, infants were first familiarized to computer-animated scenes in which a target moved with constant speed and then stopped either shortly before or after an occluder. Then, the occluder was lowered and the final scene was presented. The movement of the target was accompanied by a continuous rolling sound conveying information about the duration of the target's motion. During the test trials, the target moved behind the occluder and stopped either at the beginning (indicated by a short travel time) or at the end of the occluder (indicated by a long travel time). Infants' expectations about the target's travel distance were measured by the means of an eye tracking device before the occluder was lowered revealing the target's actual final position. Thus, analogous to methods used by several researchers (Matsuda, 1994, 2001; Wilkening, 1981, 1982), infants were given information about two dimensions (e.g., speed and time) and their estimation of the third one (e.g., distance) was measured. If infants are sensitive to the direct relation that exists between time and distance, we expected their fixation behavior to depend on the target's displacement location. That is, we expected them to spend more time looking at the beginning of the occluder after being presented with a short travel time (short distance test event) and to look longer at the far end of the occluder after being presented with a long travel time (long distance test event). To control whether infants' visual fixations were guided by their rule-based integration of time and speed and not low-level perceptual preferences (e.g., a preference for one side of the occluder); we also created a control condition. Infants in this condition were presented with exactly the same stimuli, but were not provided with the movement-linked sound (no-sound condition). Given that infants in this condition were not able to use the sound as an indicator for travel time, we expected their fixation behavior to be similar in the two types of test events (short and long distance).

4.3 Experiment 1

4.3.1 Method

Participants. Sixteen healthy and full-term 18-month-old infants (9 males, mean age = 18 months and 9 days, *SD* = 10 days) participated in the present experiment. One additional infant was tested but excluded from the sample due to insufficient eye tracking data. Additionally, eight adults were tested (2 males). In this and the following experiments, infants were recruited by telephone from a pool of families who had volunteered to take part in studies of child development. Parents signed a written consent form before taking part in the study and infants received a gift for their participation.

Apparatus. Gaze was measured by means of a TOBII X120 eye tracker (Tobii Technology, Danderyd, Sweden), a standalone eye tracker unit connected to a PC Computer (Dell Precision T5400). Data were sampled at 60 Hz with an accuracy of 0.50° visual angle. Participants sat in front of a 30" computer monitor that rested on a table with the standalone eye tracker unit positioned in front of this monitor approximately 74 cm above the floor. The eye tracker unit was positioned at a distance of 70 cm from the infant's eyes. Latency of the eye tracker was set to 30-35 ms, and time to tracking recovery was 300 ms on average. The TOBII X120 tracked both eyes simultaneously by the use of infrared diodes that produced reflection patterns on the corneas of the infants' eyes. By the means of these reflection patterns and additional visual information a three dimensional position of each cornea was computed.

Visual stimuli. Calibration was conducted using a video clip that was provided by TOBII Studio Version 1.7.2. This video clip showed a computer-animated cat that jumped within a black window (6.12º × 5.71º). The cat's jumping was accompanied by an attention-getting sound.

Stimuli were colorful computer-animated events created using Adobe Flash CS3 Professional (Adobe Systems Inc.). The target consisted of a red ball subtending 2° visual angle (see Figure 1). The target moved, accompanied by a centrally emitted sound, on a horizontal trajectory from left to right. Speed was held constant with 6.27°/s (corresponding to 7.70 cm/s). The target moved against a grey background (24.59° × 20.11°). Positioned along the horizontal trajectory were two schematic houses (10.29° × 6.14°) and a green occluder (10.29° × 3.27°) that was positioned in front of them. A short brown wall (0.61° × 3.07°) was placed along the trajectory at different positions (depending on familiarization and test event). It served as a barrier and stopped the target's movement with an appropriate collision sound.

Infants were presented with two different familiarization events. At the beginning of each familiarization, infants saw the initial scene including background, houses, and raised occluder (0.5 s). In one familiarization event (A), the target moved a distance of 7.70 cm in 1 s until its movement was stopped by the small barrier (positioned on the left of the occluder). Afterwards the occluder was lowered (1 s) and the final scene was presented (3 s). In the other event (B), the target moved a distance of 30.80 cm in 4 s until its movement was again stopped by the barrier (positioned on the right of the occluder). Immediately thereafter, the occluder was again lowered (1 s) and the final scene presented (3 s). The familiarization provided infants with information about the target's constant speed, its continuous movement behind the occluder, and the barrier's effect on the target's movement.

There were two types of test events: *Short distance* and *long distance*. The two test events differed in terms of the distance travelled by the target and the placement of the barrier. During the short distance test event, the target moved with constant speed a distance of 15.40 cm in 2 s while during the long distance test event it moved a distance of 23.10 cm in 3 s. At the beginning of each test event, infants were presented with the initial scene including background, houses and raised occluder (0.5 s). During the short distance test event, the target moved first visibly (11.64 cm in 1.5 s) and then behind the occluder where it was stopped by the barrier (after 0.5 s occluded movement). Then, it rested at this position (2 s) until the occluder was lowered (1 s), and the final scene was presented (3 s). The long distance test event was akin the short distance except that the target moved for 1.5 s behind the occluder before it was stopped by the barrier, stayed at its final position (1 s) until the occluder was lowered (1 s) and the static scene was presented (3 s). Thus, both events lasted 8.5 s. Test events differed only in the duration of the movement-linked sound (short distance: 2 s vs. long distance: 3 s). This difference in duration constitutes a ratio of 2:3. Given that 10-month-old infants are able to differentiate durations that differ in a 2:3 ratio (Brannon, Suanda, & Libertus, 2007), infants of the present study were expected to discriminate these durations. Moreover, the target's occlusion time was identical in the short and long distance test event (2.5 s), giving infants the same amount of time to anticipate the target's whereabouts.

Prior to each familiarization and test event, infants were presented with an attention-getter consisting of a colorful ball that expanded and contracted (expanded radius = 3.48°) at the left side of the screen—the position where the target would appear.

Procedure. Testing started with the infant sitting in a booster seat on their caregiver's lap. Parents were requested to close their eyes and move as less as possible during the whole testing session. Infants and their caregivers sat in front of the eye tracking unit. At the beginning of each session the experimenter presented a toy in front of the eye tracker. While the experimenter played with the infant, the eye tracker was initiated and the distance between the infant's eyes and eye tracker was adjusted. Next, the experimenter started the calibration. During calibration, the experimenter sequentially presented a video clip at nine different points of the screen (calibration was provided by TOBII Studio Version 1.7.2). If the eye tracker system reported an unsuccessful calibration (meaning that at least one point was marked for recalibration), the calibration was repeated. In general, calibration procedure lasted approximately 1-2 min. After calibration, the familiarization and test events were shown. The only source of light during the whole testing session was the computer monitor. Half of the infants started with familiarization (A), the other half with familiarization (B). Both familiarization events were presented twice in alternating order (ABAB or BABA). Immediately after the last familiarization trial, infants were exposed to a total of six test trials, each three *short* and *long distance* events presented in random order. Care was taken that a particular distance event (short or long distance) was not presented more than twice in a row. Half of the infants were first presented with a short distance, the other half with a long distance test event.

There were two conditions: *sound condition* and *no-sound condition*. In the sound condition, the movement and halt of the target was accompanied by a sound. In the no-sound condition infants saw identical stimuli, but were not exposed to the soundtrack (neither the sound of the target's movement nor the sound made by the target contacting the barrier). Thus, only infants in the sound condition were able to use the sound as an indicator for the target's travel distance and final stop behind the occluder. Half of the infants (and adults) were randomly assigned to the sound condition and half to the no-sound condition.

Data analysis. Infants' anticipatory looking behavior was measured during the target's occlusion phase (total of 2.5 s), in particular during a pre-determined time window between 3.5 s to 4.5 s after the beginning of each test event. The placement and length of this time window was selected because (a) 3.5 s after both test events' beginning, infants heard the movement-linked sound and stopping noise (during the sound condition) and (b) after 4.5 s the occluder was lowered to reveal the target's actual position. This 1-s time window was identical for all six test trials.

Two areas of interest (AOI) were created by simply dividing the area of the occluder vertically into two identical halves—AOI 1 on the left and AOI 2 to the right of the occluder. According to common practice (Gredebäck, von Hofsten, & Boudreau, 2002), we added an area of 2° visual angle to the upper and lower edge of these AOIs resulting in a total area of 10.29° × 7.27°. AOI 1 and 2 remained the same for all test events.

Infants' (and adults') fixations in s were converted into percentages of looking toward each AOI. If infants missed to fixate the AOIs in more than three test trials (i.e., more than half of the test trials), their data was excluded from the final sample. It needs to be mentioned that this was rarely the case (for only one infant in each experiment). If infants missed to fixate the AOIs in less than three test trials, the missing data points were replaced by the mean of fixation time for the particular AOI and test event (short vs. long distance) (cf. von Hofsten, Dahlström, & Frederiksson, 2005).

4.3.2 Results

Adult data. A repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables and condition (sound vs. no sound) as between-subjects variable was conducted. A significant interaction between AOIs × test events × condition was obtained, $F(1, 6) = 100.07$, $p < .001$, $\eta^2 = .94$, showing that adults' fixations depended on whether the movement-linked sound was heard or not. During the sound condition, adults correctly anticipated the final location of the target. A repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables revealed a significant interaction between AOIs × test events, $F(1, 3) = 1829.74$, $p < .001$, $\eta^2 = .99$. It was found that while adults looked significantly longer at the beginning of the occluder during the short (M = 100%, SE = 0), they looked longer at the end of the occluder during the long distance trials (M = 97.72%, SE = 2.28), $t(3) = -42.78$, $p < .001$. No other results of the ANOVA were significant. During the no-sound condition, adults' fixations did not depend on the target's displacement location. A repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables revealed a marginal significant main effect of AOIs, $F(1, 3) = 6.47$, $p = .08$, $\eta^2 = .68$. There were no other effects. Least significant difference pair-wise comparisons (LSD) revealed that adults looked by trend longer at the end of the occluder (M = 77.31%, SE = 10.74) than at the beginning (M = 22.69%, SE = 10.74).

Infant Data. Preliminary analyses revealed that infants' gender and whether they saw the short or long distance test event first did not significantly affect their fixation behavior. Thus, data were collapsed over these variables in subsequent analyses.

To reveal whether 18-month-old infants' fixations differed between the sound and no-sound condition, a repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables and condition (sound vs. no sound) as between-subjects variable was conducted. A significant interaction between AOIs × test events × condition was obtained, $F(1, 14) = 4.66$, $p < .05$, $\eta^2 = .25$, revealing that infants' fixations depended on whether the movement-linked sound was heard or not. Furthermore, there was a main effect of AOIs, $F(1, 14) = 11.27$, $p < .01$, $\eta^2 = .45$. Least significant difference pair-wise comparisons (LSD) revealed that infants of both conditions fixated AOI 1 more than AOI 2 (M = 63.23%, SE = 3.94 and M = 36.77%, SE = 3.94, respectively). There were no other significant effects.

During the sound condition, infants' anticipations depended on the target's displacement location (i.e., the short vs. long distance test event). A repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables revealed a significant interaction between AOIs × test events, $F(1, 7) = 10.62$, $p < .05$, $\eta^2 = .60$. No other analyses reached significance. Figure 2 (left side) shows that infants looked longer at the beginning of the occluder (AOI 1) during the short (*M* = 69.29%, *SE* = 7.32), and longer toward the end of the occluder (AOI 2) during the long distance trials (*M* = 56.37%, *SE* = 5.80), $t(7) = -3.26$, $p < .05$.

Furthermore, we divided infants' fixation behavior into correct and incorrect looking behavior with respect to the short and long distance test events. That is, the looking behavior for each test trial was scored as correct when (a) the infant looked longer at the beginning (AOI 1) compared to the end of the occluder (AOI 2) during a short distance test event and (b) looked longer at the end (AOI 2) compared to the beginning of the occluder (AOI 1) during a long distance test event. If the infant looked correct in all trials, the percentage score of correct looking was 100%. Reassessing the data this way revealed that infants looked correctly in 63.64% of the short distance trials (excluding 2 missing data points) and in 60.87% of the long distance trials (excluding 1 missing data point). Infants looked at the correct position of the target in 61.46% (*SE* = 4.71) of all trials, which was significantly better than expected by chance, $t(7) = 2.43$, $p < .05$.

During the no-sound condition, infants' fixations did not depend on the target's displacement location. A repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables revealed a significant main effect of AOIs, $F(1, 7) = 11.77$, $p < .05$, $\eta^2 = .63$. There were no other significant effects. Least significant difference pair-wise comparisons (LSD) revealed that infants looked longer at the beginning of the occluder (AOI 1) (*M* = 70.00%, *SE* = 5.83) than at the end (AOI 2) (*M* = 30.00%, *SE* = 5.83) (see Figure 2, right side). Thus, these findings indicate that infants' visual fixations were not influenced by the type of test event (i.e., short vs. long distance).

Again, we divided infants' fixation behavior into correct and incorrect looking behavior with respect to the short and long distance test events. Results showed that infants looked at the correct location in 71.43% of the short distance test trials (excluding 3 missing data points) and in 33.33% of the long distance trials (excluding 6 missing data points). Thus, infants looked at the correct position of the target in 53.13% (*SE* = 6.29) of all test trials, which was at chance level, $t(7) = .50$, $p > .05$.

4.3.3 Discussion

When adults and 18-month-old infants were presented with visual and auditory information about a moving target, they correctly anticipated the target's location behind the occluder. Thus, they used the movement-linked sound as an indicator for the target's travel time, and together with the information about speed were able to infer the target's displacement distance. In particular, after hearing a short travel sound, indicating that the target concluded its travels shortly after disappearing behind the occluder, they looked longer at the beginning of the occluder than at its end. In addition, after hearing a long travel sound, indicating that the target travelled to the far end of the occluder, participants looked longer at the end of the occluder. By comparison, adults' and infants' visual attention in the no-sound condition did not depend on the target's displacement location. That is, their fixation behavior was not influenced by the type of test event (short or long distance test events). Given that participants' fixation behavior in the no-sound condition differed significantly from the one during the sound condition, it is unlikely that performance in the sound condition was based on low-level perceptual preferences. Rather it seems that infants and adults in the sound condition relied on the movement-linked sound and integrated information about travel time and speed correctly to infer the target's travel distance.

Considering 18-month-olds' correct fixation behavior when the target's motion was accompanied by a movement-linked sound, one can presume that infants expected the target's movement behind the occluder to be continuous and inert. Furthermore, infants were able to distinguish between the short and long duration of the movement-linked sound (2 s vs. 3 s) which is in accordance with results of previous studies on infants' time discrimination (Brannon et al., 2007). Moreover, it seems that they were aware of the constant speed of the target and used the sound as an indicator of how far the target has travelled. Thus, the current findings suggest that infants at the age of 18 months are sensitive to the direct relationship that exists between time and distance. That is, they expect a target that travels for a long time to traverse more distance than a target that is in motion for only a short time (at the same constant speed). Therefore, they are able to infer the correct distance value after being provided with information about the other two motion-related dimensions (i.e., speed and time). This conclusion is consistent with recent findings (Möhring et al., 2012). In the next experiment, we investigate the developmental course of this sensitivity by testing 12-month-old infants' inferences about travel distance.

4.4 Experiment 2

4.4.1 Method

Participants. Sixteen healthy and full-term 12-month-old infants (7 males, mean age = 12 months and 8 days, *SD* = 8 days) participated in this experiment. One additional infant was tested but excluded from the sample due to insufficient eye tracking data.

Apparatus, Visual Stimuli, Procedure and Data analysis. The apparatus, visual stimuli, procedure and data analysis were identical to Experiment 1. Thus, infants were confronted with a target travelling different distances (short and long), while the target's motion was accompanied either by a movement-linked sound (sound condition) or not (no-sound condition). Identical to Experiment 1, missing data points were replaced by the mean of fixation time for the particular AOI and test event in which the infant failed to look.

4.4.2 Results

Preliminary analyses revealed that infants' gender and whether they saw the short or long distance test event first did not significantly affect their fixation behavior. Thus, data were collapsed over these variables in subsequent analyses.

To assess whether infants' visual fixation differed between the sound and no-sound condition, a repeated measures ANOVA with AOIs (AOI 1 vs. 2) and test events (short vs. long distance) as within-subjects variables and condition (sound vs. no sound) as between-subjects variable was conducted. A significant main effect of AOIs was obtained, $F(1, 14) = 32.43$, $p < .001$, $\eta^2 = .70$. Least significant difference pair-wise comparisons (LSD) revealed that infants of both conditions (sound and no-sound condition) looked longer at the beginning of the occluder (AOI 1) ($M = 77.67\%$, $SE = 4.86$) than at the end (AOI 2) ($M = 22.33\%$, $SE = 4.86$) (see Figure 3). No other significant results were found. Given that there was no interaction between AOIs × test events × condition ($p > .25$), the results of Experiment 2 suggest that infants' visual attention was drawn to the target's disappearance location regardless of whether infants heard the movement-linked sound or not.

4.4.3 Discussion

Infants at the age of 12 months were not able to anticipate the correct displacement location of the target. After hearing the movement-linked sound, which indicated that the target had travelled a short or long distance, infants expected the target to be located at the beginning of the occluder. However, this seemingly correct anticipation of the target's location in the short distance test events was most likely a spurious finding, given that their attention *always* lingered at the place of the target's disappearance (AOI 1) regardless of type of test event. Thus, results indicate that infants at this age show a visual anticipation behavior which is accordant to a proximity bias (i.e., infants expect the target to reappear near the position where it was last seen) (see Hood, 1995, 1998). Moreover, 12-month-old infants in the no-sound condition showed a similar visual attention pattern in that they looked reliably longer at the beginning of the occluder (AOI 1) than at the far end (AOI 2).

The findings suggest that 12-month-old infants seem not receptive to the fact that time and distance dimensions are directly linked. After being presented with values of the time and speed dimension, they were not able to adequately integrate information to correctly infer the travel distance. Thus, it seems beyond 12-month-old infants' competence to infer a longer travel distance from a longer movement-linked sound and to guide their actions (i.e., to shift gaze to the end of the occluder) accordingly.

There are some alternative explanations that may account for these findings. First, it is possible that infants at the age of 12 months were not able to use the sound as an indicator for the distance travelled. However, this explanation seems unlikely regarding findings of infants' abilities in intermodal perception. Studies investigating this issue revealed that young infants correctly relate auditory signals to different natural events. For example, they link vocal expressions with the appropriate facial expressions and accurately pair films of an approaching or departing car with their corresponding soundtrack (Spelke, 1976; Walker-Andrews & Lennon, 1985; Walker, 1982). Most importantly, Srinivasan and Carey (2010) illustrated recently that 9-month-old infants were able to bind particular spatial lengths with the appropriate temporal durations, indicating an early functional overlap between spatial and temporal representations. In addition, the lengthy familiarization phase of the present study provided infants repeatedly with the fact that sound and movement were linked. Thus, taking these considerations into account, it seems unlikely that infants were not able to bind sound and movement.

Second, results of the present study show that infants' anticipations during the short distance test events were seemingly correct, while they failed to anticipate correctly during the long distance test events. Although these correct inferences during the short distance test events are likely a spurious finding, it might be informative to discuss differences between the two types of test events (short vs. long distance). The only variation between these two events (aside from the target's final position) is that the duration of the movement-linked sound was 1 s longer during the long distance compared to the short distance test event. Thus, infants needed to represent the target's movement for 1 s longer during the long distance test event. One could argue that this longer sustainment of motion representations exceeds 12-month-old infants' capacity. However this line of argumentation seems unlikely given that 6- to 12-month-old infants are able to successfully update spatio-temporal information about an object's movement during even longer occlusion periods than 1 s (e.g., Gredebäck & von Hofsten, 2004; Gredebäck, et al., 2002).

Overall, infants at the age of 12 months are not able to correctly infer values of the distance dimension when presented with values of the speed and time dimension. Therefore, our results suggest that infants at this age do not have a rule-based understanding about TSD interrelations and thus are not sensitive to the direct link between time and distance dimensions.

4.5 General Discussion

The present experiments investigated whether adults and infants correctly anticipate the travel distance of a moving object after they were provided with information about its travel time and speed. We demonstrated that adults and 18-month-olds, but not 12-month-olds, are able to correctly anticipate an object's final location behind an occluder when information about travel time was available (sound condition). Furthermore, no age group differentiated between the short and long distance test event when information about travel time was withheld (no-sound condition).

These findings suggest that infants as young as 18 months are able to use and integrate information about an object's travel time and speed to infer values of the corresponding distance dimension. Thus, infants at this age are aware that time and distance dimensions are directly related and expected a shorter/longer travel distance after hearing a shorter/longer duration of the movement-linked sound (when speed is held constant). This finding is in accordance with a recent study of Möhring and colleagues (2012) which suggests that 18-month-old infants are able to correctly infer an object's travel distance in an action-based task.

By contrast, the 12-month-old infants of the present study were not able to correctly infer values of the distance dimension. Instead, 12-month-old infants' fixations lingered always at the target's disappearance location. This behavior supports the assumption that infants expected the target to be near the position where it was last seen. This type of looking behavior is coherent to a proximity bias and thus, indicates the use of a very simple strategy. Such regressions to simpler strategies are often found in infant and toddler studies (Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Hood, 1995, 1998) and generally suggest that infants were not able to inhibit a predominant response. With regards to the present experiment, it seems that infants were not able to suppress a prepotent response—namely, to expect the object to be there, where it was last seen. In any case, 12-month-olds' failure to infer values of the distance dimension suggests that younger infants were not able to correctly integrate time and speed values. Thus, important changes in the ability to infer distance from time and speed seem to take place between 12 and 18 months of age.

It is possible that this developmental change is a function of infants' improvements in self-initiated locomotion. While infants start to crawl around the age of 9 months, they begin to walk around their first birthday. Once this developmental milestone has been reached, they intensely exercise their new motor skills, and thus experience their own as well as others (including objects') movements in space more directly. It is conceivable that these experiences affect and transform infants' spatial knowledge (Newcombe & Huttenlocher, 2000). Crawling as the first independent or self-initiated movement has been investigated intensively, especially with regards to its relations to other aspects of development. For example, it was found that locomotor status (e.g., pre- versus crawling) has an impact on infants' spatial cognition (Bai & Bertenthal, 1992), action perception of others (van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008), and their social and emotional development (Campos et al., 2000; Campos, Bertenthal, & Kermoian, 1992).

In one study by Acredolo, Adams, and Goodwyn (1984) the effects of self-initiated movements on spatial knowledge were investigated. In this study, 12- to 18-month-old infants were presented with a Plexiglas box that contained two hiding wells. The back wall of the box was removable and the front wall had an opening. During the training phase, the child was seated at the back of the box with the Plexiglas wall removed. Upon hiding an object in one of the wells, infants were encouraged to retrieve the object. After several successful retrievals, the back wall was replaced (denying direct access to the hiding wells), the toy again hidden, and the child was encouraged to search. Infants were either invited to find the toy themselves by moving around the box (active movement), or were carried by their mother to the opening in the front wall (passive movement). While 12-month-olds' searches were more accurate after experiencing active, self-produced rather than passive movement, this effect disappeared at the age of 18 months. However, in subsequent experiments, the authors demonstrated that in their task it was not active movement per se that facilitated 12-month-olds' searching responses but rather their visual tracking behavior. That is, 12-month-old infants' success in finding the object was constrained to their possibility to consistently keep their eyes on the object's new position. In contrast, 18-month-olds were able to find the object without permanently tracking it. In line with our findings, Acredolo and colleagues note that "... at 18 month the infants were able to mentally represent the simple spatial relations […] and easily predict the consequences […]" (p. 325). Therefore, it seems that the crucial factor for correct search behavior lies in the precision of infants' mental representations concerning spatio-temporal information. Our results and the ones of Acredolo et al. (1984) are consistent with what Piaget claimed about infants' spatial behavior during Stage 6 (Piaget, 1954). Piaget described that at this stage, infants around the age of 18 months are able to represent object locations even when some of the object's movements are hidden.

Overall, we were able to show that infants at the age of 18 months were able to correctly integrate information about time and speed and accurately inferred values of the distance dimension. That is, infants were sensitive to the fact that a shorter/longer travel time is directly related to less/more travel distance indicating that infants at this age have a rule-based understanding about time-speed-distance interrelations. By contrast, 12-month-olds' inferences relied on the use of a simple strategy (i.e., the object will be there, where it was last seen). It might be argued that older infants learned to successfully inhibit this proponent response. Following this line of argumentation, our results are coherent to conclusions made by Diamond (1991) in that cognitive development is not only the acquisition of knowledge (e.g., an understanding about time-speed-distance interrelations) but also the ability to inhibit previous reactions (like a proximity bias). In various studies, researchers were able to show that with increased maturation of the prefrontal cortex, infants were able to suppress predominant responses (e.g., Diamond & Doar, 1989, Diamond & Goldman-Rakic, 1989). Thus, it is conceivable that maturation of the prefrontal cortex may at least partially or additionally be responsible for the better performance of the 18 months old infants.

In conclusion, the present study is the first to show that infants' rule-based understanding about TSD interrelations seems to be present at least at the age of 18 months and thus, extends and qualifies results of previous studies in a number of ways (Spelke et al., 1995; von Hofsten et al., 1998, 2000; Wilkening, 1981). Future studies may investigate infants' sensitivity to other relations that are inherent in the time-speed-distance-triad (e.g., the direct relation between speed and distance).

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Figure Captions

Figure 1. Examples of the familiarization and test stimuli used in both experiments. Depicted is the target's final position after the occluder was lowered. The dashed lines represent the movement of the target. The stimuli presented to infants were in color.

Figure 2. Eighteen-month-old infants' mean fixation behavior (%) toward AOI 1 and AOI 2 during the short and long distance test event. Infants' fixation in the sound condition is presented on the left side; infants' fixation in the no-sound condition on the right side. Error bars indicate standard errors.

Figure 3. Twelve-month-old infants' mean fixation behavior (%) toward AOI 1 and AOI 2 during the short and long distance test event. Infants' fixation in the sound condition is presented on the left side; infants' fixation in the no-sound condition on the right side. Error bars indicate standard errors.

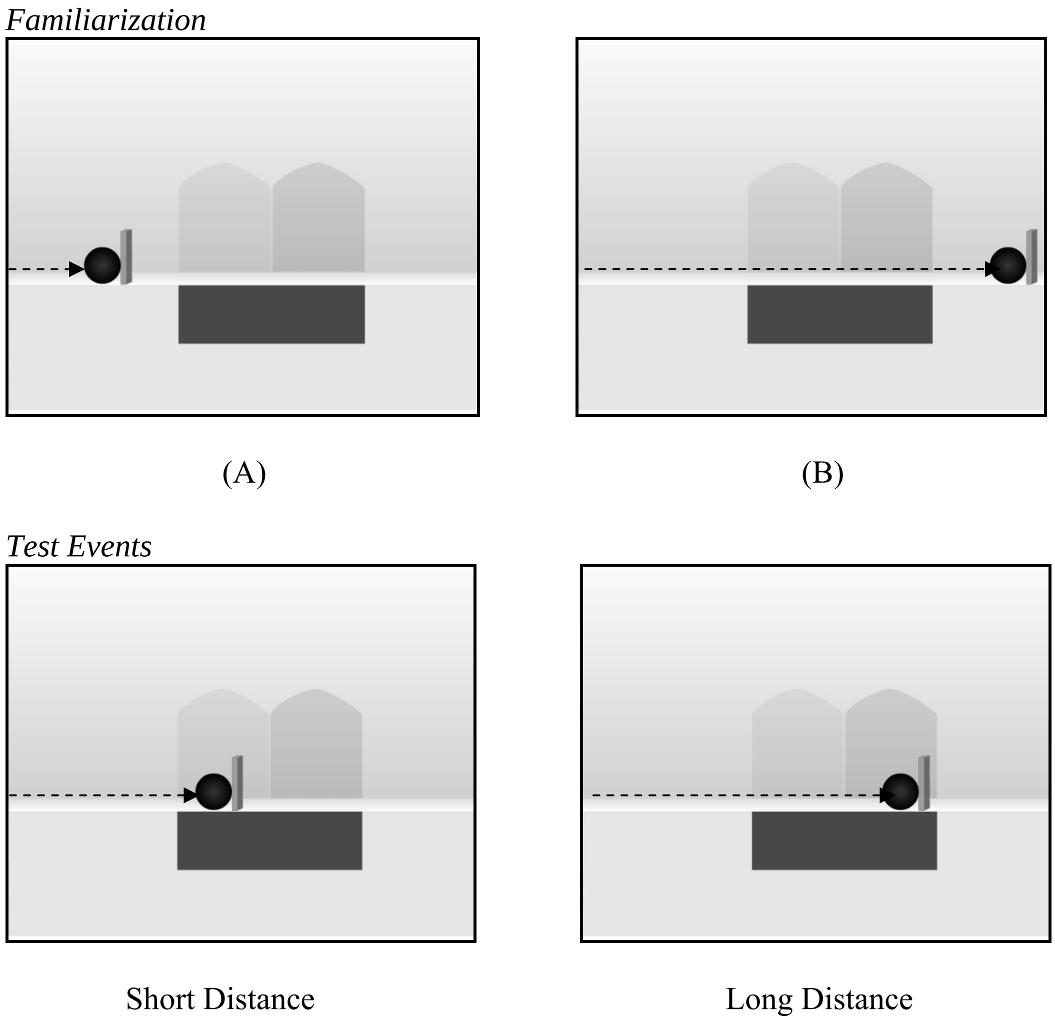
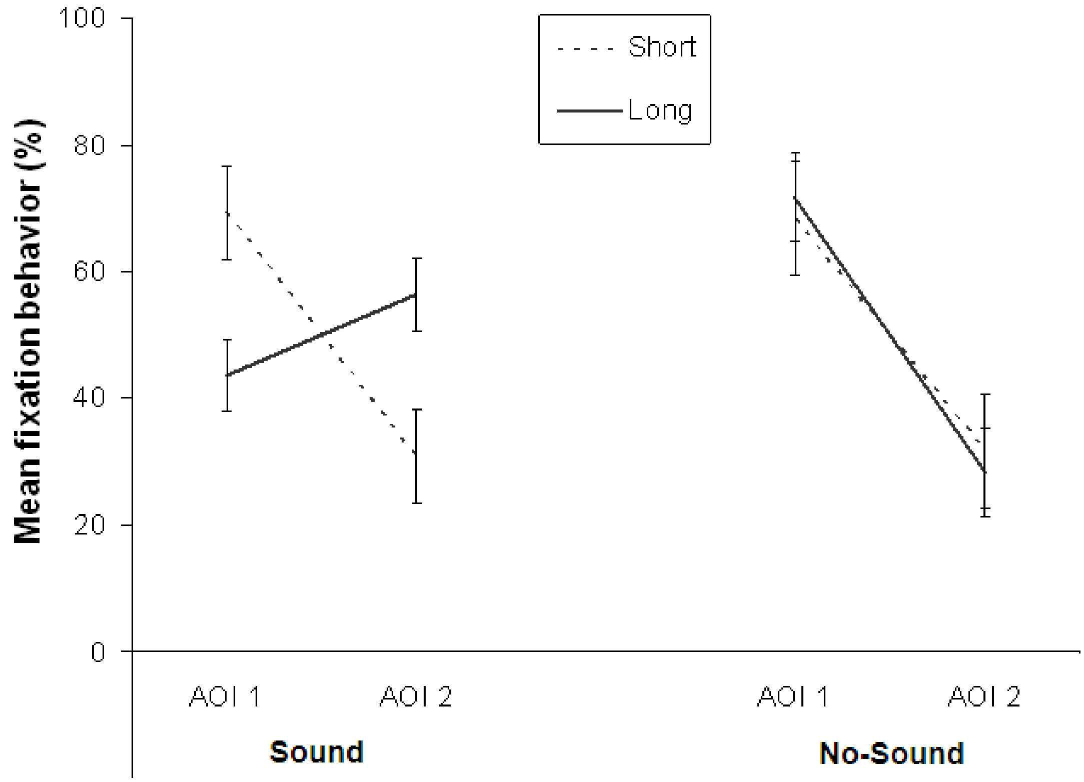

Familiarization
(A)
(B)
Test Events
Short Distance
Long Distance

Figure 1.



100
80
60
40
20
0
Mean fixation behavior (%)
Short
Long
AOI 1
AOI 2
AOI 1
AOI 2
Sound
No-Sound

Figure 2.

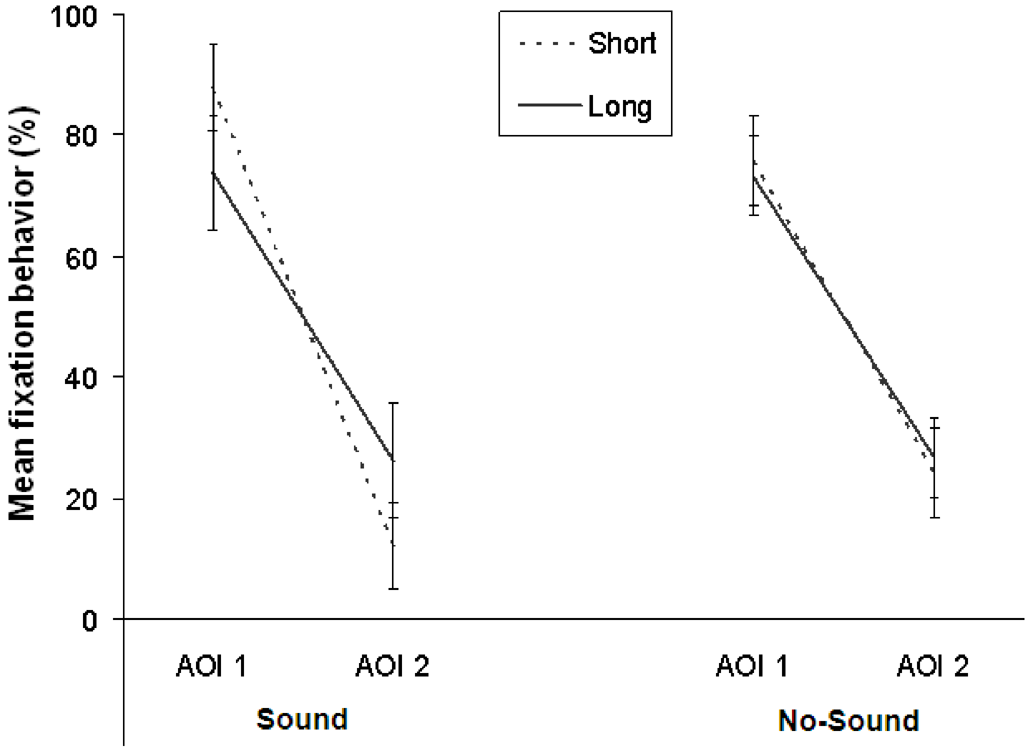

100
80
60
40
20
0
Mean fixation behavior (%)
Short
Long
AOI 1
AOI 2
Sound
AOI 1
AOI 2
No-Sound

Figure 3.

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PROFESSIONAL POSITIONS

03/2008 – current	Assistant and Doctoral student Dissertation thesis: *"Infants' sensitivity to time-speed-distance interrelations".* Supervisor: Prof. Dr. F. Wilkening

UNIVERSITY AND SCHOOL EDUCATION

09/2002 – 02/2008	Studies in psychology at the University of Leipzig, Germany
02/2008	Diploma in psychology (MSc)
04/2007	Diploma Thesis *"Die physikalische Welt des Säuglinges: Sensitivität zu den funktionalen Beziehungen von Zeit, Distanz und Geschwindigkeit".* Supervisors: Prof. Dr. E. Schröger (University of Leipzig) and Dr. E. Bertin (University of Zurich)
09/2004	Pre-Diploma (Bachelor) in psychology
09/1999 – 08/2002	Apprenticeship as hospital nurse with theoretical training at nurse's training school Aschersleben/Stassfurt and vocational training at the Hospital Köthen/Anhalt.
08/1999	High school diploma ("Abitur")

INTERNSHIPS AND RESEARCH ASSISTANCE

09/2007 – 02/2008	Research assistant at the Department of Cognitive and Developmental Psychology, University of Zurich, Switzerland. Supervisors: Prof. Dr. F. Wilkening and Dr. E. Bertin
05/2007 – 06/2007	Research internship at the Department “Cognition and Action” at the Max-Planck-Institute for Cognitive Neurosciences, Leipzig, Germany. Supervisors: Dr. Martina Rieger and Dr. Christina Massen
02/2006 – 07/2007	Research assistant at the Department “Cognition and Action” at the Max-Planck-Institute for Cognitive Neurosciences, Leipzig, Germany. Supervisors: Dr. Peter Keller and Dr. Masami Ishihara
11/2004 – 08/2005	Research assistant at the Department “Cultural Ontogeny” at the Max-Planck-Institute for Evolutionary Anthropology, Leipzig, Germany. Supervisor: Dr. Tricia Striano

SCHOLARSHIPS

08/2008 – current	Fellow of the International Max Planck Research School "The Life Course: Evolutionary and Ontogenetic Dynamic”.
06/2008 – 12/2009	Member of the Peer-Mentoring Program for the academic career development of young researchers at the University of Zurich.
09/2007 – 11/2007	Scholarship of the German Academic Exchange Service (Deutscher Akademischer Austausch Dienst).

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